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Measures of Ecological Integrity for Salmonid Streams on Department of Defense Facilities in the Pacific Northwest: Current Watershed Conditions and Management Recommendations

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EXECUTIVE SUMMARY

Stream ecosystems and their riparian ecotones are some of the most important natural resource areas in the Pacific Northwest (PNW) region. These resources are also among the most threatened by population growth and development. Several Department of Defense (DoD) installations in the region contain valuable aquatic habitat that supports threatened or endangered species of wildlife, including multiple species of salmonids and other aquatic biota. A number of military bases in the PNW region contain ecologically valuable and sensitive aquatic resources that sustain this valuable native biota. These sensitive areas on military bases need to be properly managed to protect the natural resources they hold while supporting military operational capability within the base boundaries.

Military bases are subject to many of the same development related impacts found in the surrounding communities. At the same time, there are also several unique land-use activities associated only with military operations. As is the case with watersheds throughout the PNW in general, the cumulative impacts of military and non-military operations have degraded the quality of salmonid habitat within the base boundaries. This being said, there are still a number of high-quality aquatic ecosystems remaining on DoD lands within the PNW region. The main reason for the focus on the PNW is the current and pending federal listings of several species salmonids under the Endangered Species Act (ESA). These ESA listings have the potential to impact all aspects of military operations, from routine base operations to military training exercises. Under Section 7 of the ESA, military bases must show they are making a significant effort to protect, enhance, and restore "critical habitat" for all listed species.

Declining stocks of native salmon and the listing of Puget Sound chinook as threatened under the Endangered Species Act have intensified interest in assessing instream habitat conditions in PNW streams. Little quantitative information about the habitat condition of most regional streams is available. This is true for streams within DoD jurisdiction as well. From June to November of 2000, the University of Washington conducted field surveys on military bases in the PNW. The goals of the habitat assessment project were threefold: (1) characterize the habitat quality, primarily for salmonids; (2) establish a baseline for future evaluation of trends in habitat quality and watershed function; and (3) inform the process of prioritizing areas for restoration and preservation.

The results of the habitat assessments indicate that channel and habitat structure of a number of the segments in most streams are frequently degraded relative to values from published "properly functioning conditions" for the Puget Sound or the PNW region. For example, bankfull width to depth ratios are often larger than prescribed properly functioning conditions ratios, suggesting that channel dynamics are unstable. Pool habitat frequencies are lower than standards and of low quality in most segments. This decreased slow water "rearing" habitat may limit juvenile carrying capacity as well as hinder upstream migration by adult salmon. In addition, instream habitat complexity and large woody debris (LWD) abundance and quality are significantly degraded, exacerbating rearing habitat deficiencies and compounding the hydro-geomorphic instability. The low amounts of instream LWD may be partially responsible for the low pool frequency. LWD

frequency was closely related to pool frequency in most study streams as it is in undisturbed streams of the PNW.

These data suggest that processes creating natural habitat structure may be changed from natural conditions. Analysis of basin land cover reveals less forested and increasingly impervious cover, as well as a significant loss of wetlands, which has been shown to alter the basin hydrologic regime. This change in basin hydrology leads to destabilization of channel morphology. Riparian vegetation also seldom resembled natural conditions and was nearly completely depleted of sources of high quality, coniferous large woody debris (LWD). Dominant riparian vegetation often included landscaping, invasives, and young deciduous forest.

These data are important baseline information for any restoration projects that might occur in the basins, as well as for monitoring changes in habitat quality. Data contained herein may be used for a limiting factor analysis or for other habitat related projects. The data collected may also be analyzed at a finer spatial scale to inform project planning at more localized sites or among basins for regional project planning. Land use planning, military operational planning, and stormwater management planning in these basins can also benefit by using this data.

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PROJECT OBJECTIVES

The overall goal of this research project was to determine a suite of ecological-based indicators for stream and wetland ecosystems to measure environmental change resulting from a shift in natural disturbance regime due primarily to the cumulative effects of watershed development in general, and military operations in particular. The study investigated a range of physical, chemical, and biological parameters that could be used as tools for assessing changes in natural ecosystem structure and function resulting from military activities within the study watersheds. A major objective of this study was also to provide baseline measurements of watershed and instream habitat conditions for use in conservation and restoration activities on DoD facilities in response to ESA requirements. The information obtained from this report can be used by natural resource managers to guide stewardship of aquatic ecosystems and the salmonid species they support. This information will also be useful in restoring or enhancing salmonid habitat impacted by past military operations, as well as managing future activities to minimize their impact on aquatic ecosystems.

Specific objectives accomplished during this research include:

- Identification and quantification of the unique impacts of military operations on ecological integrity of salmonid-supporting ecosystems in the PNW.
- Evaluation of aquatic ecosystem assessment protocols used in the region for applicability to military installations and their associated natural resources.
- Development of a standard protocol for assessing the ecological integrity of salmonid-bearing streams on DoD facilities.
- Generation of a regional database relating the degree of watershed disturbance and ecological integrity to salmonid utilization, including abundance and species composition, and instream habitat quantity and quality. Establish the linkage between the landscape level stressor (military operations and landscape development) and the ecological integrity of the affected aquatic resources. Stream surveys will include riparian corridor characterization, water quality monitoring, instream habitat surveys, hydrologic monitoring, geomorphic surveys, and biological monitoring (salmonids and benthic macroinvertebrates). Natural, reference sites were also identified and quantified as the basis for establishing restoration target conditions.
- Development of a management framework for stream ecosystem protection and restoration based on active management for natural ecological integrity. This framework will guide military and civilian resource managers in interpreting measurable ecological parameters toward design of effective ecosystem rehabilitation, enhancement, and preservation efforts. In addition, recommendations were developed for the various military operations in order to minimize their impact on aquatic resources. Relationships among all variables measured in the study, including instream habitat characteristics, aquatic community parameters, riparian characteristics, and measures of military land-use/operational impact were analyzed.

A secondary objective of the project was to evaluate the existing stormwater management infrastructure, including structural and nonstructural best management practices (BMP). Special attention was given to current surface and stormwater management problems identified by personnel of the base Public Works (PW) Departments. Based on this evaluation, integrated surface and stormwater management (SWM) recommendations were developed. SWM recommendations are built around a watershed-based, resource-driven approach for protecting aquatic ecosystems from the impact of human activities.

BACKGROUND

Over the past century, the historic range of Pacific salmon in the Pacific Northwest (PNW) has been reduced significantly (*Nehlsen* et al. 1991). The resulting decline in salmonid abundance and biodiversity has led to the listing of several PNW salmon stocks under the ESA. There is no single cause the decline in this valuable natural resource, but one of the most significant contributors has been the cumulative impacts of human land-use activities on the aquatic ecosystems that have traditionally supported the native salmon populations (*NRC*, 1996). Activities such as timber harvest, mining, agriculture, grazing, dams, fishing, hatcheries, and development have all contributed to the "salmon problem" as it exists today. Urbanization (residential, commercial, and industrial development) has been especially hard on small streams in the lowland ecoregions of the PNW (*May et al*., 1997). These small streams provide critical habitat for all freshwater life stages of salmonids and were once highly productive systems. Stream habitat loss and watershed degradation are often cited as important limiting factors to salmon productivity and diversity (*Nehlsen et al*., 1991; *NRC*, 1996; *Spence et al*., 1996). Currently, a number of native salmonid species are being considered for listing under the ESA. Prescribed salmon recovery efforts have the potential to impact land-use activities throughout the region, including military installations in the Puget Sound Lowland (PSL) eco-region.

The effects of watershed urbanization on freshwater resources throughout the U.S. are well documented (*Leopold*, 1968; *Hammer*, 1972; *Hollis*, 1975; *Klein*, 1979; *Arnold et al*., 1982; *Schueler*, 1995; *Roesner*, 1997). They include extensive changes in basin hydrologic cycle, channel morphology, and physio-chemical water quality. The cumulative effect of these alterations has produced an instream habitat that is significantly different from that in which salmonids and associated fauna have evolved. In addition, development pressure has a negative impact on riparian forests and wetlands, which are essential to natural stream functioning. Considerable evidence of these effects exists from many studies of urban streams in the PNW (*Perkins*, 1982; *Richey*, 1982; *Steward*, 1983; *Scott et al*., 1986; *Booth*, 1990; *Booth*, 1991; *Booth and Reinelt*, 1993; *Taylor*, 1993; *Horner et al*., 1997; *May et al*., 1997; *Horner and May*, 1999). The cumulative effects of watershed urbanization in the PSL region have resulted in a loss of natural forest and wetland cover, as well as a significant increase in impervious surface area. Riparian forests, floodplains, and off-channel wetlands have also been severely degraded by the incremental encroachment of residential and commercial development. All of these "landscape-level" alterations to the natural environment have resulted in significant changes in the hydrologic regime, water quality, and physical habitat of the aquatic ecosystems of the region. The end result of these modifications has been a

general decline in biodiversity and productivity, which has been especially noticeable in the native salmon populations.

Agricultural land use also affects stream health, although research indicates that the effects are not as catastrophic as those caused by urbanization (*Wang et al*., 1997; *Allan et al*., 1997; *Steedman*, 1988). Degradation in rural streams is associated with loss of riparian forest, channelization and diking, sedimentation, and moderate nutrient enrichment. In some watersheds, biotic integrity does not begin to decline until > 50% agricultural land use in the watershed (*Wang et al*., 1997; *Allan et al*., 1997). Water quality problems including nutrient enrichment and riparian forest loss, rather than hydrologic disturbance, may be the most important concern in watersheds dominated by agricultural land use.

Research in the Puget Sound and elsewhere in the U.S. has focused on establishing linkages between watershed development and the ecological integrity of freshwater ecosystems, as well as the causes and effects of water quality degradation in streams and wetlands. These studies have identified several key findings:

1. There is no single cause for the decline of water resource conditions in urbanizing watersheds. Instead, it is the cumulative effects of multiple stressors that are responsible for reduced stream ecological integrity.
2. Imperviousness, while not a perfect "yardstick," appears to be a useful predictor of overall watershed condition. Only streams with very low levels of watershed imperviousness appear to be capable of retaining a natural level of ecological integrity.
3. There are multiple scales of impact that are operating within each watershed. These include landscape impacts including the loss of natural forest cover and the increase in imperviousness throughout the watershed. There are also local effects such as water diversions, stream channelization, streambank hardening, and culvert installation. All these stressors contribute to the overall cumulative impact.
4. Another important scale of influence for aquatic ecosystem health is the integrity of the riparian ecotone that surrounds most streams and wetlands under natural conditions. This *riparian integrity* includes the extent, continuity, and quality of the native riparian vegetation.
5. There is no clear threshold of urbanization below which there exists a "no-effect" condition. Instead, there appears to be a relatively continuous decline in almost all measures of water quality, physical habitat, and biological integrity.
6. While the decline in ecological integrity is relatively continuous and is consistent for all parameters, the impact on physical conditions appears to be more pronounced earlier in the urbanization process than chemical degradation. It is generally accepted that it is the shift in hydrologic conditions that is the driving force behind physical changes in urban stream/wetland ecosystems. These impacts include streambank erosion, channel incision, and channel widening.

7. Measures of biological integrity are the most responsive and integrative indicators of overall aquatic ecosystem health.
8. Our conventional SWM strategy, which relies almost exclusively on mitigation of development using engineered BMPs alone, does not appear to be effective in protecting the ecological integrity of our aquatic resources as is required by the Clean Water Act (CWA). Under current development and mitigation strategies, it is apparent that downstream changes to both the structure and function of aquatic ecosystems is inevitable unless limits are instituted on the extent and distribution of watershed development.
9. Rehabilitation and enhancement efforts should be concentrated on streams draining watersheds with low to moderate development. Restoring the natural hydrologic regime should be a primary goal. At the highest levels of urbanization, natural ecological function may not be possible. Although recovery to near-pristine conditions cannot be expected in all developed stream basins, innovative mitigation efforts should nevertheless continue in an effort to improve stream quality to a level supportive of natural biota. Because of the cumulative effects of past and current land-use practices, some habitat enhancement will be required to accomplish rehabilitation goals in all PSL streams, regardless of present watershed development level.

Landscape Alterations

Mature coniferous forests characterize the natural landscape of the PNW. Under natural land-cover conditions, the hydrologic regime is dominated by evapo-transpiration, infiltration, sub-surface flow, and groundwater recharge (see Figure 1). Little or no stormwater run-off is produced except during very large storm events (*Booth*, 1991). In most cases, the native, coniferous-dominated forest can absorb precipitation through a combination of canopy interception, evapo-transpiration, and infiltration by the highly absorbent forest soils. It is this complex forest landscape with its evergreen canopy, diverse understory, and the highly absorbent forest "duff" layer of organic matter that is responsible for the characteristic sub-surface flow hydrologic regime of this region (see Figure 1). A mature, coniferous forest can intercept upwards of 40% of annual precipitation, utilizing the moisture for plant growth and returning much of it back into the atmosphere via evapo-transpiration (*Booth*, 1991). The precipitation that does reach the ground may also be captured by understory vegetation or groundcover. The remainder is absorbed into the rich organic matter that makes up the upper soil horizon. This natural organic material is not only highly absorbent, but it also facilitates infiltration of the precipitation into the lower soil layers. Due to the most recent period of glacial activity, the underlying soils of the region generally have a poor infiltration capacity. In addition to the native forest, the natural watersheds of the region typically have extensive headwater wetlands that also absorb precipitation and slowly release it to streams throughout the dryer portions of the year. The resultant hydrologic regime is one where streams and rivers respond slowly to rainfall events and maintain their baseflow throughout the year due to groundwater sources and wetland recharge. This is the hydrologic regime that the salmonid species of the region have evolved to over thousands of years.

Figure 1. *Typical annual water budget in a natural, forested PNW watershed*

Development has radically changed the landscape in watersheds of the PNW. Mature forests and wetlands have been lost as land is cleared for agriculture and urban development. The natural land-cover described above has been replaced by more and more impervious surfaces, including roads, rooftops, and lawns. As impervious surface area increases with urbanization, the sub-surface dominated hydrologic regime shifts to one dominated by surface run-off (Figure 2). This increase in run-off comes mainly at the expense of groundwater recharge and subsurface interflow. This shift in hydrologic regime can result in a loss of streamflow during summer low flow periods and a loss of aquifer recharge. During storm events, the increased volume of run-off can overwhelm the natural drainage system and result in severe channel erosion and rapidly fluctuating streamflow conditions. These impacts can have serious implications for both aquatic biota and humans living in the watershed. Urban development also adds numerous artificial channels to the natural stream system. The most common of these artificial channels are roadside drainage-ditches and stormwater drainage outfalls. This increase in drainage density (DD) contributes to the problem of increased run-off getting to the stream system too rapidly. These man-made features also act as conduits for surface run-off and non-point source (NPS) pollution. Little or no infiltration or storage is associated with these artificial stormwater conveyance systems and as a result the run-off volume is dramatically increased. In addition to increased run-off volume and more frequent high-flow events, there is a degradation of water quality due to urban pollutants entrained in the stormwater run-off. The cumulative effect of this alteration of the natural hydrologic regime and the degradation in water quality is a loss of instream salmonid habitat and a decrease in biodiversity within the aquatic ecosystems of the PNW (*May et al*., 1997).

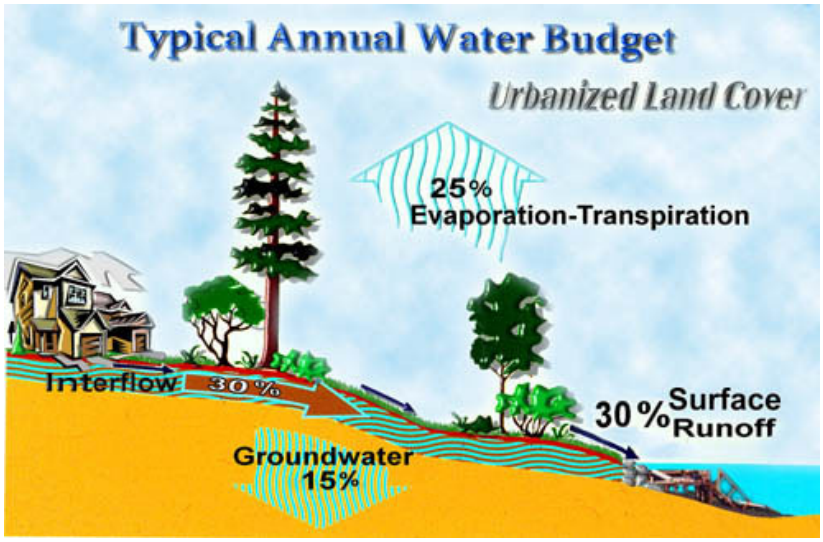

Figure 2. *Typical annual water budget in a developed PNW watershed*

The stream-riparian ecosystems of the PNW encompass the most important freshwater habitat for endangered salmon as well as a myriad of terrestrial and aquatic biota (*Knutson and Naef*, 1997). A wide, nearly continuous corridor of mature forests, off-channel wetlands, and complex floodplain areas characterizes natural stream-riparian ecosystems of the region (*Naiman and Bilby*, 1998). Native riparian forests of the region are typically dominated by a complex, multi-layered forest of mature conifers, mixed with patches of alder where disturbance has occurred in the recent past (*Gregory et al*., 1991). The riparian forest also includes a complex, dense, and diverse understory and groundcover vegetation. In addition, the extensive upper soil-layer of forest duff provides vital water retention and filtering capacity to the ecosystem. A typical PNW natural riparian corridor also includes a floodplain area, channel migration zone (CMZ), and numerous off-channel wetlands. Natural floodplains, CMZ, and riparian wetlands are critical components of a properly functioning aquatic ecosystem (*Naiman and Bilby*, 1998). Organic debris and vegetation from riparian forests also provide a majority of the organic carbon and nutrients that support the aquatic ecosystem food web in these small lowland streams. In short, the riparian community (vegetation and wildlife) directly influences the physical, chemical, and biological conditions of the aquatic ecosystem. Reciprocally, the aquatic ecosystem affects the structure and function of the riparian community. Anadromous salmonids provide a rich, seasonal food resource that directly affects the ecological integrity of both aquatic and terrestrial food webs. The potential contribution of nutrients from decomposing salmon carcasses to the forest was historically quite significant (*Cederholm et al*., 1989; *Knutson and Naef*, 1997; *Willson et al*., 1998; *Cederholm et al*., 1999). The presence of this seasonally abundant nutrient resource has also had a hand in shaping the evolution of the stream-riparian ecosystem (*Willson, et al*., 1998). The aquatic ecosystems of the region are very closely linked ecohogically with the surrounding terrestrial ecosystems. Therefore, any human impacts that destroy or degrade habitat in the stream-riparian corridor, or reduce the abundance

and diversity of wildlife that are associated with anadromous salmonids, has the potential to weaken the ecological linkages in this complex ecosystem.

In addition to the characteristics of the riparian forest described above, the most commonly recognized functions of the riparian corridor include the following (*Gregory et al*., 1991; *Naiman and Bilby*, 1998; *FISRWG*, 1998):

- Providing canopy-cover shade necessary to maintain cool stream temperatures required by salmonids and other aquatic biota. Regulation of sunlight and microclimate for the stream-riparian ecosystem.
- Providing organic debris, leaf litter, and other allochthonous inputs that are a critical component of many stream food webs, especially in headwater reaches.
- Stabilizing streambanks, minimizing streambank erosion, and reducing the occurrence of landslides, but still providing stream gravel recruitment.
- Interacting with the stream channel in the floodplain and CMZ. Retention of floodwaters. Reduction of fine sediment input into the stream system through floodplain sediment retention and vegetative filtering.
- Facilitate the exchange of groundwater and surface water in the riparian floodplain and stream hyporheic zone.
- Filtering and vegetative uptake of nutrients and pollutants from groundwater and stormwater run-off.
- Providing recruitment of LWD into the stream channel. LWD is the primary instream structural element that functions as a hydraulic roughness element to moderate streamflows. LWD also serves a pool forming function, providing critical salmonid rearing, flow-refugia, and enhanced instream habitat diversity.
- Providing critical wildlife habitat including migration corridors, feeding and watering habitat, and refuge areas during upland disturbance events. Primary habitat for aquatic habitat modifiers such as beaver and many other terrestrial predators or scavengers associated with salmonid populations.

The cumulative effects of watershed urbanization on streams are well documented. They include extensive changes in basin hydrologic regime, channel morphology, and physicochemical water quality. The cumulative effects of these alterations produce an instream habitat considerably different from that in which salmonids and associated fauna evolved. In addition, development pressure has a negative impact on native riparian forests and wetlands, which are intimately involved in stream ecosystem functioning. Much evidence of these effects exists from studies of urban streams in the Puget Sound region (*Richey*, 1982; *Scott et al*. 1986, *Booth and Reinelt*, 1993; *Horner et al*., 1997; *May et al*., 1997). During the last of these regional studies of urbanizing watersheds, it became apparent that so-called riparian buffers, if designed and maintained so as to emulate natural riparian conditions, could have a significant mitigating influence on the ecological degradation of streams and wetlands in urbanizing watersheds of the PSL region (*May et al*., 1997). This was reflected in higher than expected levels of biotic integrity in those stream reaches with wide, continuous, and naturally vegetated buffers

(including intact headwater and off-channel wetlands). Based on the results of the initial PSL stream studies (*May et al*., 1997), the term riparian integrity was adopted to describe the conditions found in natural PSL stream-riparian ecosystems. These properly functioning conditions should serve as a template for conservation and recovery of riparian areas. As used here, riparian integrity includes both structural and functional elements characteristic of the natural stream-riparian ecosystem.

Buffer width or extent is often the sole criteria by which most stream-riparian corridor management areas are generally defined. Buffers can be "fixed" or "variable" in width. Fixed-width buffers are generally the products of political compromise between protecting a natural resource and minimizing the impact on development and private-property rights. Buffers of this type, unless conservatively designed and managed, often fail to support all the ecological functions of the riparian corridor. Variable-width buffers have the potential to be more ecologically based, but are difficult to administer by jurisdictions.

Impacts of human activities on stream-riparian ecosystems are numerous and highly variable. The complex mosaic of land use in developing watersheds results in multiple stressors impacting the stream-riparian ecosystem. The characteristics of the stream-riparian ecosystem will also influence the extent and intensity of the human-induced disturbance. Streams in watersheds dominated by rural development will have different impacts than those in suburban or urban watersheds.

Variables such as stream size, location within the watershed, stream gradient, valley configuration, watershed topography, soil type, and others all combine to make some stream-riparian ecosystems more or less sensitive to surrounding human impacts. For example, a stream with an extensive floodplain area or active CMZ will react quite differently than a stream within a deep, steep-walled ravine. It stands to reason then, that appropriate buffer size will depend on the spatial area necessary to maintain the desired riparian functions and on the land-use activities that are influencing the stream-riparian ecosystem. For example, a wider buffer may be required in situations where high-intensity land-use is found, than in areas of low-intensity land-use. Similarly, all else being equal, a sensitive tributary stream used by salmonids for spawning and rearing may require larger buffers than does a mainstem stream used only as a migration corridor. In general, urban riparian buffers have not been consistently protected or well managed (*Schueler*, 1995; *Wenger*, 1999). This is certainly true of the PSL region where riparian buffer *encroachment* is all too common (*May et al*., 1997).

Of equal importance to the width or extent of the riparian corridor is the quality of the riparian area in terms of vegetation type, species diversity, physical condition, and maturity. Ideally, the riparian corridor in a developing or developed watershed should mirror that found in the natural ecosystems of that region. As was discussed earlier, mature, coniferous-dominated forests with a mosaic of young forest and riparian wetlands characterize natural riparian corridors. Due to the cumulative impacts of past and present land-use, this is often not the case. The riparian quality of the stream corridor is as important as the width or extent in determining how well a particular riparian area performs all of the functions required of it. The current vegetative composition and maturity should be factored into any riparian management or buffer width design effort. Areas dominated by mature, naturally complex forest have a much higher conservation

potential than disturbed areas, young stands of native forest, or exotic vegetation. These mature and naturally diverse riparian areas also perform their required functions more efficiently and tend to be more resilient in recovering from disturbance (*Naiman and Bilby*, 1998). Past land-use activities in the PSL (timber harvest, road construction, and agricultural activities) have significantly impacted the riparian forests of the region (*Horner and May*, 1999). As a result, many riparian forests in urbanizing watersheds are dominated by relatively young stands of alder and maple rather than the mixed-mature forests that characterize natural riparian communities of the PSL (*May et al*., 1997).

Riparian corridor connectivity is also an ecologically critical and often under-emphasized component of riparian integrity. Natural riparian corridors in the PNW are nearly continuous throughout the stream-riparian ecosystem (*Naiman and Bilby*, 1998). In addition to buffer width and quality, management of the riparian corridor should focus on minimizing fragmentation of the riparian corridor. Road crossings, utility right-of-ways, and other breaks in the riparian corridor effectively reduce the buffer width to zero and provide a conduit for run-off and pollutants to enter the stream (*Schueler*, 1995; *May et al*., 1997; *Weller et al*., 1998). Breaks in the riparian corridor should be kept to a minimum and all breaks should be designed for minimal stormwater and other impacts (*Horner and May*, 1999). Floodplain connectivity is also critical to a properly functioning stream-riparian ecosystem (*Naiman and Bilby*, 1998; *FISRWG*, 1998). This means that the active CMZ and floodplain should be included in the designated riparian management zone (RMZ). Both from an ecological and public safety perspective, development should excluded from the RMZ. In general, encroachment of developing areas should be prevented from impacting the structure or function of the stream-riparian ecosystem. This can be done via public education and by clear delineation of the RMZ (*Schueler*, 1995b).

Instream Habitat Degradation

Instream salmonid habitat is characterized by physical and chemical attributes of the stream environment during the juvenile life-stage (from emergence to the smolt migration). Physio-chemical water quality is generally taken to include temperature, dissolved oxygen (DO), suspended sediment (turbidity), nutrient levels, toxic compounds, and other pollutants. One of the most influential physical characteristics of the stream is the flow (discharge) regime. The disturbance regime in PNW streams is primarily discharge-driven. Salmonids are sensitive to changes in streamflow and tend to key their life-cycle related movements to local discharge regimes. Watershed development can significantly alter the hydrologic regime due to increases in impervious surface area, loss of natural forest infiltration capacity, and modification of the stream drainage network (*Booth*, 1991). The resultant increase in peak discharge magnitude and frequency can have serious negative impacts on salmonids and instream habitat.

Most stream fishes utilize specific instream habitat types during different life-stages (*Bisson et al*., 1982). Salmonids are no exception to this rule. Within salmonid populations, competition and territoriality plays an important role in stream habitat selection and utilization. This is particularly true of the juvenile life-stage. When food is limited, such density-dependent interactions result in habitat partitioning of sympatric populations and intra-species age-classes (*Glova*, 1984). In general, juvenile coho salmon prefer deep, slow-water pools formed by LWD (logs and root-wads), whereas juvenile steelhead prefer riffles and lateral scour pools with faster water and cover

provided by LWD, overhanging vegetation, or undercut banks (*Bisson et al*., 1982). Cutthroat are often competitively displaced and are opportunistic in their choice of habitat types, able to survive in pools, riffles, or glides provided cover (LWD) is present (*Hartman*, 1965; *Bisson et al*., 1982; *Glova*, 1984; *Bugert et al*., 1991; *Heggenes et al*., 1991). Juvenile salmonids move within their stream system to take advantage of seasonal environmental changes (*Bustard and Narver*, 1975). Juvenile coho often seek refuge from high stormflows and over-winter in off-channel (floodplain) ponds or wetlands (*Tschaplinski and Hartman*, 1983; *Hartmann and Brown*, 1987).

Adequate pool area and residual depth, along with sufficient cover, are the keys to successful salmonid rearing. Studies have consistently indicated that the optimum pool-riffle ratio for coho production and over-winter survival is approximately 1:1 (*McMahon*, 1983; *McMahon and Hartman*, 1989; *Nickelson et al*., 1992). Coho often shift habitat preferences as the seasons change, due primarily to changes in flow and usable stream area. In winter, coho prefer off-channel, backwater or wetland pools and in summer they show a preference for main-channel pools formed by LWD (*McMahon and Hartman*, 1989; *Nawa et al*., 1990; *Nickelson et al*., 1992). Most studies have concluded that winter habitat is the most limiting factor in streams impacted by human activities within the watershed (*Nickelson et al*., 1992). This is mainly due to the lack of instream habitat complexity normally provided by the abundant LWD found in natural streams. With adequate LWD and complex habitat features less fish are lost due to flooding washout and there tends to be greater overall fish diversity (*Pearsons et al*., 1992). Timber harvest, road-building, and urban development are all activities that tend to reduce LWD and instream pool habitat.

High-quality rearing habitat is critical for the survival of juvenile salmonids from emergence to smolt migration. Adequate total pool area and residual depth along with sufficient cover are necessary for successful juvenile salmonid rearing (*Bjorn and Reiser*, 1991). Juvenile chinook, for example, utilize high-quality pools (good cover and relatively deep) when they are in transition from emergence to mortification (*Bjorn and Reiser*, 1991). Salmonids often shift their habitat preferences seasonally, primarily due to changes in flow and usable stream area. For example, juvenile coho prefer off-channel, backwater, or wetland/ beaver ponds during the winter, and show a preference for main-channel pools formed by large woody debris in the summer months (*Nawa et al*., 1990; *Nickelson et al*., 1992; *Peterson et al*., 1992). In addition, adult chinook require deep staging pools for their upstream migration (*Giger*, 1973).

LWD performs numerous instream functions contributing to the formation of high quality aquatic rearing habitat. LWD is a key component for maintaining a high degree of habitat complexity or spatial heterogeneity in streams (*Maser et al*. 1988). LWD maintains the hydraulic stability of critical instream habitat features, especially pools (*Bilby and Ward*, 1991). LWD dissipates hydraulic energy during peak flows, providing high-flow refuge for salmonids (*Bilby*, 1984). In addition, LWD stabilizes streambeds by minimizing scour and provides excellent cover and habitat diversity (*Harmon et al*., 1986) for salmonids. With the loss of LWD in the channel, stream morphology shifts away from the characteristic pool-riffle habitat to a more simplified, glide-dominant channel form, with a subsequent decrease in available rearing (pool) habitat. Large woody debris (LWD) is an integral and ubiquitous component of streams in forested watersheds of the PNW.

Instream woody debris influences the physical, chemical, and biological processes occurring within the stream. LWD traps allochthonous organic matter, which represents a substantial portion of the energy base of the stream (*Bilby and Likens*, 1980; *Bilby*, 1981; *Bilby*, 1984). LWD also influences the transport and storage of sediment within the channel (*Nakamura and Swanson*, 1993). In the PNW, variations in channel sinuosity, gradient, and width are often regulated by LWD (*Nakamura and Swanson*, 1993). LWD can have a significant local influence on channel form, including formation of mid-channel bars, meander cutoffs, and the pool-riffle sequence (*Keller and Swanson*, 1979). Riparian forests play a key role in the control of stream channel morphologic features. These biophysical interactions are particularly important to the stream ecosystems of the PNW (*Rot*, 1995). Riparian forests also stabilize the active floodplain and are the primary source of LWD. In turn, LWD plays a key role in the formation of riparian forests. LWD deposited in the active channel provides sites for vegetative colonization on forested islands and in floodplain areas (*Fetherston et al*., 1995).

In the streams of the PSL, organic debris enters the stream channel as a result of bank erosion, hillslope mass-wasting events, and blow-downs. The zone from which LWD is supplied to the channel varies as a function of riparian forest composition, valley landform, and stream characteristics (*Steinblums et al*., 1984; *Grette*, 1985; *Murphy and Koski*, 1989; *Fetherston et al*., 1995). Much of the woody debris entering small unconstrained channels, such as those common to the PSL, is introduced as a result of undercutting of trees located on streambanks (*Grette*, 1985). It has been found that 70–90% of riparian zone input of LWD originates from within 30 m of the stream channel, but as the forest becomes more mature and conifer-dominated, the proportion of input from beyond 30 m increases (*Van Sickle and Gregory*, 1990).

In general, smaller stream channels (low-order) contain the largest quantity (numbers of pieces) of LWD and have the highest LWD frequency (pieces/length of stream). In larger (higher order) channels, woody debris is more easily transported (*Bisson et al*., 1987). Larger stream channels tend to have larger sized LWD and also a greater frequency of debris jams and accumulations of LWD (*Bilby and Ward*, 1991). The quantity and distribution of LWD is also influenced by the riparian forest composition and age. Streams flowing through mature stands of cedar, hemlock, and fir in the PNW, tend to contain a larger quantity of woody debris with larger average-size pieces than streams within young and/or deciduous riparian zones (*Bilby and Ward*, 1991). LWD derived from conifers, especially western red cedar, not only tends to be larger than deciduous species (predominantly alder and maple), thus reducing the chance of being washed downstream, but also have significantly greater resistance to decay, resulting in increased longevity as instream structural components (*Harmon et al*., 1986).

Human activities within the riparian zone have been shown to have adverse impacts on LWD abundance, distribution, and function (*Sedell et al*., 1984; *Grette*, 1985; *Murphy et al*., 1986; *Murphy and Koski*, 1989; *Bilby and Ward*, 1991). Even if instream debris is left undisturbed during clearing of riparian forests, the quantity and quality of LWD declines over time because second-growth forests or urbanized riparian zones are unable to provide sufficient debris to replace that which is washed downstream or naturally decays (*Grette*, 1985; *Andrus et al*., 1988; *Murphy and Koski*, 1989). Under natural conditions, the quantity, size distribution, and species composition of organic debris

varies considerably depending on stream size and riparian forest structure (*Bilby and Ward*, 1989). Depletion rates are inversely proportional to LWD diameter, showing the importance of mature riparian trees to the maintenance of instream structure (*Murphy an Koski*, 1989). Recovery of LWD recruitment potential to natural levels (i.e., pre-logging or urban clearing) can take more than 100 years (*Grette*, 1985; *Bisson et al*., 1987; *Bilby and Ward*, 1989). In general, small undeveloped streams tend to have an abundance of LWD, while impacted channels tend to contain less LWD, smaller pieces, and have more LWD concentrated in debris jams.

There is no other structural component as important as LWD to salmonid habitat in PNW streams. LWD provides structure to the stream ecosystem and critical habitat for salmonids (*Andrus et al*., 1988). LWD performs many critical functions in forested, lowland streams. This includes maintaining the hydraulic stability of key habitat features, especially pools (*Bilby and Ward*, 1991). LWD also dissipates flow energy during peak flow events providing high-flow refuge, protecting streambanks from erosion and thus reducing sediment generation (*Bilby*, 1984), helps stabilize streambeds to minimize scour, and provides cover and habitat diversity (*Harmon et al*., 1986). Human activities, such as timber harvesting within the riparian forests of PNW streams, have an adverse impact on LWD, instream habitat quality, and juvenile salmonid diversity (*Bryant*, 1983; *Murphy et al*., 1986; *Hicks et al*., 1991; *Reeves et al*., 1993). Urbanization has similar impacts, but may be even longer lasting, especially from a hydrological standpoint. In addition to the loss of hydraulic roughness (flow energy buffer) and channel stabilizing capacity, the reduction of in-channel LWD has a major effect on instream habitat complexity and diversity. LWD is the single most important pool-forming structure in streams of the Pacific Coast and PSL eco-regions (*Grette*, 1985; *Crispin et al*., 1993). LWD also provides the most desirable cover for coho salmon and other salmonids, especially during winter, high-flow periods (*McMahon and Hartman*, 1989). With the loss of inchannel structure, there is a morphological shift away from the characteristic pool-riffle habitat to a glide-dominant channel form. There is a decrease in rearing (pool) habitat both from a quantitative and qualitative perspective. Coho in small streams have a very strong preference for structurally complex cover and low-flow microhabitats associated with organic debris (*McMahon and Hartman*, 1989). Communities of aquatic biota in general, and salmonids in particular, depend on instream habitat complexity provided by LWD (*Harmon et al*., 1986). There is no question that the complexity of LWD accumulations in small lowland streams are important to salmonid populations.

The sand, gravel, and cobble that makes up the substrata of PNW streams also plays a vital role in determining how the ecosystem of the stream will function. Substrata size distribution and spatial arrangement influences (physical) channel hydraulics. The substrata provides benthic habitat for macroinvertebrates and bottom-dwelling fish (sculpins). Periphyton and macrophytes also depend on the substrata composition. With respect to salmonids, the streambed substrata is critical to the level of spawning success, incubation, and survival to emergence. Each species of salmonids has specific preferences for gravel size and composition for spawning (*Kondolf and Wolman*, 1993), but all salmonids require spawning gravels that are highly permeable and relatively free of fine sediment (*McNeil*, 1966; *Chapman*, 1988; *Crisp and Carling*, 1989). In the process of building their redds, salmonids actually ‘winnow” the fine sediment from the

streambed gravels thus improving the interstitial flow of water to the incubating eggs within the redd (*Kondolf et al*., 1993). Survival to alevin emergence has been shown to be strongly correlated to the percentage of fine sediment (fines) in the substratum (*Chapman*, 1988). Excess fine sediment also has an adverse impact on habitat suitability and survival for benthic macroinvertebrates (*Cordone and Kelley*, 1961; *Cline et al*., 1982; *Lemly*, 1982). The percentage of fine sediment (% fines) < 0.85 mm in diameter as determined by standard substrate sampling methods (McNeil Sampler) and sorted using standard sieves, is the most widely accepted measure of spawning gravel quality. Elevated levels of fine sediment in spawning gravels have been associated with timber-harvest activities, mining, grazing, and other human activities (*Beschta*, 1978; *Cederholm and Salo*, 1979; *Shirazi and Seim*, 1981; *Everest et al*., 1987; *Campbell and Doeg*, 1989; *Scrivner and Brownlee*, 1989; *Eaglin and Hubert*, 1993).

Anthropogenic activities in the watershed can also have detrimental effects on salmonid spawning habitat (*Bisson et al*., 1992). Some studies indicate that the optimum, natural pool to riffle ratio for salmonid production and over-winter survival is one that is relatively balanced (*Nickelson et al*., 1992). In addition, streambed substrate is also critical to spawning success, incubation, and survival to emergence for salmonids. Each salmonid species has a specific preference for spawning habitat conditions (*Kondolf and Wolman*, 1993), but all salmonids require spawning gravels that are highly permeable and relatively free of fine sediment (*McNeil*, 1966; *Chapman*, 1988; *Crisp and Carling*, 1989). The substrate also provides benthic habitat for macroinvertebrates, freshwater mussels, and bottom-dwelling fish such as sculpin. Increased over-land flow (including run-off) and stream bank erosion caused by anthropogenic activities in the watershed contribute to sediment deposition in the interstitial spaces of spawning gravels. This sediment suffocates biota reliant on well-oxygenated intragravel flow (*Hartman and Brown*, 1987). The % fines in PSL streams is also strongly correlated with the level of urbanization in the upstream basin (*May et al*., 1997).

Ecosystem Management

Ecosystem management is an evolving, holistic approach to natural resource management and restoration. The foundation of this approach is based on the scientific principles of conservation biology and landscape ecology. The overall goal of the ecosystem approach is the conservation of biodiversity through the management of structural components and functional processes within the ecosystem. A basic assumption underlying this approach is that proper stewardship of the ecosystem as a whole will result in the conservation of all species including those currently endangered or threatened by human activities. A key principle of this form of resource management is that humans are an integral part of the ecosystem because their values and priorities drive their interaction with the environment. Ecosystem management is the guidance of human activities that are together ecologically sustainable, economically viable, culturally supportive, and socially acceptable now and in the future (*Grumbine*, 1994). In addition to its scientific foundation, it is also understood that the natural capacity of the ecosystem and the value-driven constraints of society limit the success of ecosystem management. Another key element critical to the success of this approach is the need for adaptive management. The willingness to try innovative techniques, effectiveness monitoring, and a timely feedback mechanism are vital components of ecosystem management programs. Ecosystem management is

therefore not only a scientific-based framework, but is an integration of ecological science and value-driven, socio-political components that is designed to achieve a goal of long-term protection of ecological integrity.

Our scientific understanding of the ecosystem provides the conceptual framework needed to guide the development of a coherent natural resources management plan. This ecological framework describes the structure and boundaries of the ecosystem, as well as the critical processes that constitute the functional elements of the natural system. This framework provides a context for interpreting scientific data, aids in defining problems, setting management goals, and establishing restoration objectives. In short, scientific knowledge should serve as a "compass" to guide the effective management of our natural resources (*Lee*, 1993).

It must be understood that natural systems exist in a state of *dynamic equilibrium*, continuously adapting to a changing environment. In general, ecosystems are not as predictable as human engineered systems. In addition, our knowledge of ecosystems is continuously improving, but will always contain some uncertainty. Given this scientific uncertainty, management efforts need to be flexible, well monitored, and should always incorporate a feedback mechanism into the process. Environmental policy and management objectives need to be modified in response to new scientific information or an improved understanding of ecosystem dynamics. This adaptive approach assumes that scientific knowledge is evolving and emphasizes management as a learning process, where incorporating feedback from earlier decisions allows resource managers to remain flexible in their future actions (*Lee*, 1993; *Grumbine*, 1994; *Healey*, 1998). Ecosystem management is an evolving program that should be continually revised as new empirical data become available and ecological theories are refined.

In addition to the ecological limits identified by scientific research, there are also socio-economic constraints on ecosystem management. Cultural values and political compromise shape environmental policy. Successful ecosystem management requires the implementation of environmentally sustainable activities that balance socio-economic human needs and ecological functions (*Healey*, 1998). Humans and our technologies are integral components of the ecosystem. However, in the last 100 years, technology has generally out-paced our ability to manage it. Science and politics can, if balanced properly, be harnessed to attain a goal of long-term sustainability (*Lee*, 1993). To accomplish that objective, society must move away from uncontrolled growth and the unintended changes and ecosystem degradation that accompany development activities. Instead, ecosystem change should be a result of conscious choice after considering the pros and cons of each option available. Social learning, adaptive management, and political change are key. Under environmental uncertainty, natural resource management policies should be viewed as experiments and must be modified based on learning from experience and scientific feedback (*Lee*, 1993). For social learning to become institutionalized, citizens at all levels of society must be involved with the ecosystem management process.

Watershed Management

Water is a significant natural resource. The aquatic ecosystems that depend on adequate, high-quality water are important from both a socioeconomic and an ecological

perspective. In the PNW, salmon and the stream ecosystems that support them are especially important to the regional economy, as cultural icons, and as symbols of the quality of life people associate with this part of the country. Ecosystem management is based on the principle of preserving ecological integrity while maintaining sustainable benefits for human society. This presupposes that some human land use activity will be part of the landscape of the ecosystem. Under our current natural resource policies and environmental regulations, there is often an inherent conflict between ecological integrity and resource utilization.

The watershed, or catchment, is the basic unit of water resources management. A watershed encompasses the drainage area of each individual surface-water network (lake, stream, or river). A watershed is the area of land that water flows across or under on its way to a river, lake, or ocean (Figure 3). It includes all surface fresh water and adjacent estuaries or nearshore areas. Watersheds are nature's way of dividing up the landscape. Rivers, lakes, estuaries, wetlands, streams, even the oceans can serve as drainage basins for the land adjacent to them. Ground water aquifers serve the same purpose for the land above them. The actions of people who live within a watershed affect the health of the waters that drain into it.

John Wesley Powell—scientist, geographer, and leader of the first expedition through the Grand Canyon in 1869—perhaps described it best when he said that a watershed is:

> *...that area of land, a bounded hydrologic system, within which all living things are inextricably linked by their common water course and where, as humans settled, simple logic demanded that they become part of the community.*

Watersheds involve much more than simply water resources. They encompass whole or parts of terrestrial ecosystems as well. The obvious implication of this is that watershed management is an integral component of ecosystem management. Also implicit in Powell's definition is the fact that human influences are a key component of the developed landscape and the watershed in which that land-use activity exists. Activities at any location in the watershed may have a negative impact on downstream resources. The watershed management approach has proven to be effective in minimizing the effects of development on sensitive aquatic resources (*Schueler*, 1995).

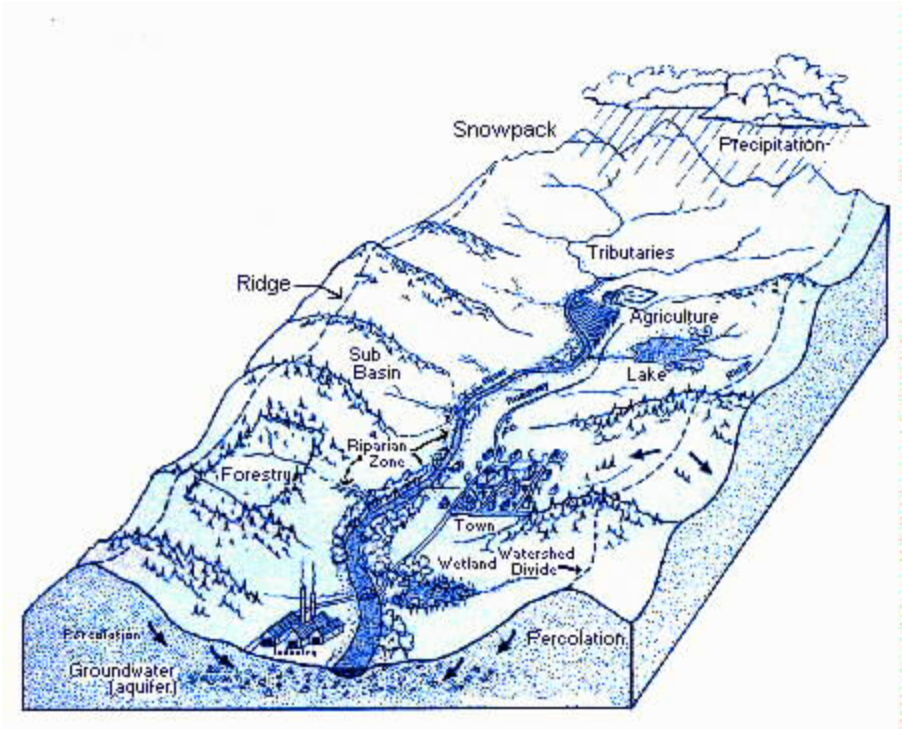

Figure 3. *Typical watershed*

Watershed ecology is the study of watersheds as ecosystems, primarily the analysis of interacting biotic and abiotic components within a watershed's boundaries. Watershed ecology is essential knowledge for watershed managers because it teaches us that watersheds have structural and functional characteristics that can influence how human and natural communities coexist within them. The gross structure of a watershed—its headwaters area, side slopes, valley floor, and water body, as well as its soils, minerals, native plants and animals—are, in one sense, raw material for all the human activities that may potentially occur there. The watershed's natural processes of rainfall run-off, groundwater recharge, sediment transport, plant succession, and many others—provide beneficial services when functioning properly, but may cause disasters when misunderstood and disrupted. It is crucial for people to understand watersheds and how they work before they make decisions or take actions that may affect important watershed structural or functional characteristics.

The physical template of watershed structure is ultimately determined by varying combinations of climatic, geomorphic, and hydrologic processes. The three elements of the physical template and other factors also interact significantly in determining the structure and composition of a watershed and its biotic communities. As a result of different combinations of these formative processes, different types of watersheds are created. Concepts of basic ecology provide the vocabulary to understand and describe the ecological setting of watersheds and the interaction of biotic components with the physical template. Natural systems such as watersheds have interacting components that

together perform work (e.g., transport sediment, water, and energy) and generate products (e.g., form new physical structures like floodplains or channels, and form biological communities and new energy outputs). In a natural system, interactions make the whole greater than the sum of its parts. Each of the physical and biological components of watersheds if they existed separately would not be capable of generating the work and the products that the intact watershed system can generate.

The natural systems concept is key to watershed management because it emphasizes that a watershed, as a natural system, is more than just a variety of natural resources coincidentally occurring in one place. Severely degraded watersheds may have lost several of their components and functions and provide fewer benefits to human and natural communities as a result. Thus it is clear that recognizing the natural system and working toward protecting the system's critical components and functions are key to sustainable watershed management. It is vitally important for watershed managers to appreciate the natural processes at work, and how they are beneficial to our communities as well as our ecosystems. Even more, it is crucial to recognize how change affects watersheds and can jeopardize these benefits in very costly ways, when a normal change becomes great enough to be a change of concern.

Change is a natural, essential feature of watersheds. Being able to identify different change processes, understand the differences between natural and human influences on watershed changes, and recognize a change of concern are all critical for effective watershed management. Watershed change, however, can be very complicated to understand and manage when many human and natural causes of change interact as they often do. In many cases, periodic disturbance is required to foster ecological processes (e.g., flooding promotes nutrient cycling in riparian soils), or to complete the life cycles of various organisms (e.g., many coniferous trees rely on fire for seed release and dispersal). A certain amount of change is therefore unavoidable, essential and desirable in watershed ecosystems. For this reason, a key element in any concept of ecosystem health is an ecosystem's ability to evolve over time and to self-regulate following changes.

Aquatic ecosystems are inherently dynamic in nature. Natural systems are often described as being in a state of dynamic equilibrium, meaning that while they are not static, they do have an equilibrium condition around which they fluctuate based on natural variability. The driving force behind this ever-changing condition is the disturbance regime of the ecosystem. Natural disturbances include such things as fire, flooding, volcanic activity, earthquakes, storms, and other geologic or climatic events. These natural disturbances can be regional in scale, such as a hurricane, or local, such a landslide. Natural disturbances are often described as “pulse” events because they disturb the system for a relatively short period of time and then return to pre-disturbance conditions. These events typically modify the ecosystem in a variety of ways and over a range of scales. The ecosystem will respond to natural disturbances in a variety of ways. For example, a stream system subject to a flood event will often change course or be altered geomorphically, changing its shape or channel configuration. A flood can also destroy or alter aquatic habitat, causing some organisms to be stressed or even extirpated from a system. At the same time, habitat for other biota may be created by the same disturbance. In other words, the ecosystem evolves and adapts to the changing conditions over time.

In addition to natural disturbance events that alter the ecosystem conditions, anthropogenic (human) disturbances can also impact ecosystems. Most human caused disturbances can be described as "stress" events as opposed to the "pulsed' nature of the natural disturbance regime. By this it is meant that human disturbances are usually more frequent or even continuous and often increase in intensity over time. Anthropogenic disturbances also tend to be wider in scale than most natural disturbances. An example of this is development or land use.

The quality of water resources depends on numerous physical, chemical, and biological variables. The sum of these physical, chemical, and biological factors is often referred to as ecological integrity. A natural level of ecological integrity is synonymous with a high level of stream quality. Healthy, self-sustaining salmon and trout populations require high stream quality. Stream quality (ecological integrity) includes the physiochemical quality of the water, the hydrologic regime in the watershed, the conditions of instream habitat, and the riparian infrastructure. In general, the degradation of stream quality is directly related to the level of human activity (development) within a watershed. Because of its gradual, incremental nature and the delay between development activity and environmental impact, development is difficult to manage. In addition, watersheds often cross jurisdictional boundaries, which complicates the decision-making and management process. Watershed management is most effective if it is resource driven and based on a sound scientific foundation.

The U.S. Environmental Protection Agency (US-EPA) defines a watershed protection approach as a strategy for effectively protecting and restoring aquatic ecosystems and protecting human health. This strategy has as its premise that many water quality and ecosystem problems are best solved at the watershed level rather than at the individual water-body or discharger level. Although watershed protection concepts were included in the promulagation of the CWA in 1972, recent court and regulatory rulemaking developments have taken these sustainable land management and watershed protection practices from "suggested" projects to compliance requirements with specific implementation timelines. According to the U.S. EPA (www.epa.gov/OWOW/watershed), the watershed protection approach is made up of these key components:

- A focus on a critical resource(s) such as salmonids, drinking water supply, recreation, or shellfish.
- A geographic focus based on the natural boundaries of the drainage system and surrounding landscape. These boundaries may cross state, local, or tribal jurisdictional boundaries.
- Adaptive management based on sound scientific data, tools, and techniques. This requires developing an intimate knowledge of the watershed, identifying and prioritizing problems, and devising action plans and solutions.
- Community-building, including inter- and intra-government partnerships with citizen groups, the business community, and landowners. It is important to involve all stakeholders in the process of designing and implementing watershed action plans.

The core principles of watershed management include:

- Watersheds are natural systems that we can work with.
- Watershed management is continuous and needs a multi-disciplinary approach.
- A watershed management framework supports partnering, using sound science, taking well-planned actions and achieving results.
- A flexible approach is always needed.
- Watershed protection is generally more effective than restoration.

In addition to the requirements laid out in the CWA, there are numerous executive orders and the *Unified Federal Policy for Ensuring a Watershed Approach to Federal Lands and Resource Management* that direct DoD installations to adopt a watershed protection approach to site management. Table 1 provides a summary of these laws, executive orders and policies and the impact they have on installation site management practices. By conducting a watershed assessment, installations will meet the requirements of the CWA and the *Unified Federal Policy for Ensuring a Watershed Approach to Federal Lands and Resource Management*.

Table 1. *Federal laws, executive orders, agreements, and memoranda of understanding (MOU) related to watershed management*

Category	Title
Federal laws	Clean Water Act (CWA)
	Safe Drinking Water Act (SDWA)
	Coastal Zone Management Act of 1972 (CZMA)
	Sikes Act
	Clean Air Act (CAA)
	Comprehensive Environmental Restoration, Cleanup and Liability Act (CERCLA)
	Emergency Planning and Community Right-to-Know Act (EPCRA)
	Endangered Species Act (ESA)
	Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)
	National Environmental Policy Act (NEPA)
	Resource Conservation and Recovery Act (RCRA)
Executive orders	13148, Greening the Government Through Leadership in Environmental Management
	13112, Invasive Species
	13093, American Heritage Rivers
	12902, Energy Efficiency and Water Conservation at Federal Facilities
	12088, Federal Compliance with Pollution Control Standards
	11990, Protection of Wetlands
	11988, Floodplain Management
	11593, Protection and Enhancement of the Cultural Environment
	11514, Protection and Enhancement of Environmental Quality
	11288, Prevention, Control, and Abatement of Water Pollution by Federal Activities.
Policies and voluntary agreements	Clean Water Action Plan
	Unified Federal Watershed Policy
	Unified Watershed Assessments
	Index of Watershed Indicators
	Federal Multi-Agency Source Water Agreement
	Special Tributary Strategy for Federal Lands in the District of Columbia
	Chesapeake 2000: A Watershed Partnership Agreement
	Agreement of Federal Agencies on Ecosystem Management in the Chesapeake Bay
DoD MOUs	MOU to Foster the Ecosystem Approach
	MOU Between the U.S. Environmental Protection Agency and the U.S. Department of Defense with Respect to Integrated Pest Management

STUDY AREA

The "landscape" of salmon consists of the Pacific Ocean, the nearshore and estuary environment of the Puget Sound and PNW coast, and the freshwater rivers, streams, wetlands, and lakes of the region. This is an extensive and complex array of ecosystems to manage. The DoD facilities of the PNW are a unique and valuable component of this salmon landscape. Because of its concentration of DoD military facilities, the focus of this PNW research project was the Puget Sound region. This is the location of the majority of military bases in the region and the area where human activities are having the largest impact on native salmon populations. From an ecological perspective, the area is classified as the Puget Sound lowland (PSL) eco-region. This region is home to several military bases, including the following (Figure 4):

Fort Lewis U.S. Army Base

McChord Air Force Base

Puget Sound Naval Shipyard (PSNS)

Bangor Naval Submarine Base

Keyport Naval Engineering Station

Jim Creek Naval Communications Station

Indian Island Naval Weapons Station

Everett Naval Station

Whidbey Island Naval Air Station

As part of the early phases of this project, an initial survey of natural resources was done for all of these Puget Sound DoD facilities. Only Fort Lewis Army Base, McChord Air Force Base, Bangor Submarine Base, and Jim Creek Naval Communications Station were found to have significant freshwater aquatic ecosystems that supported native salmonid populations. These bases were selected as the study areas for the project (Figure 4).

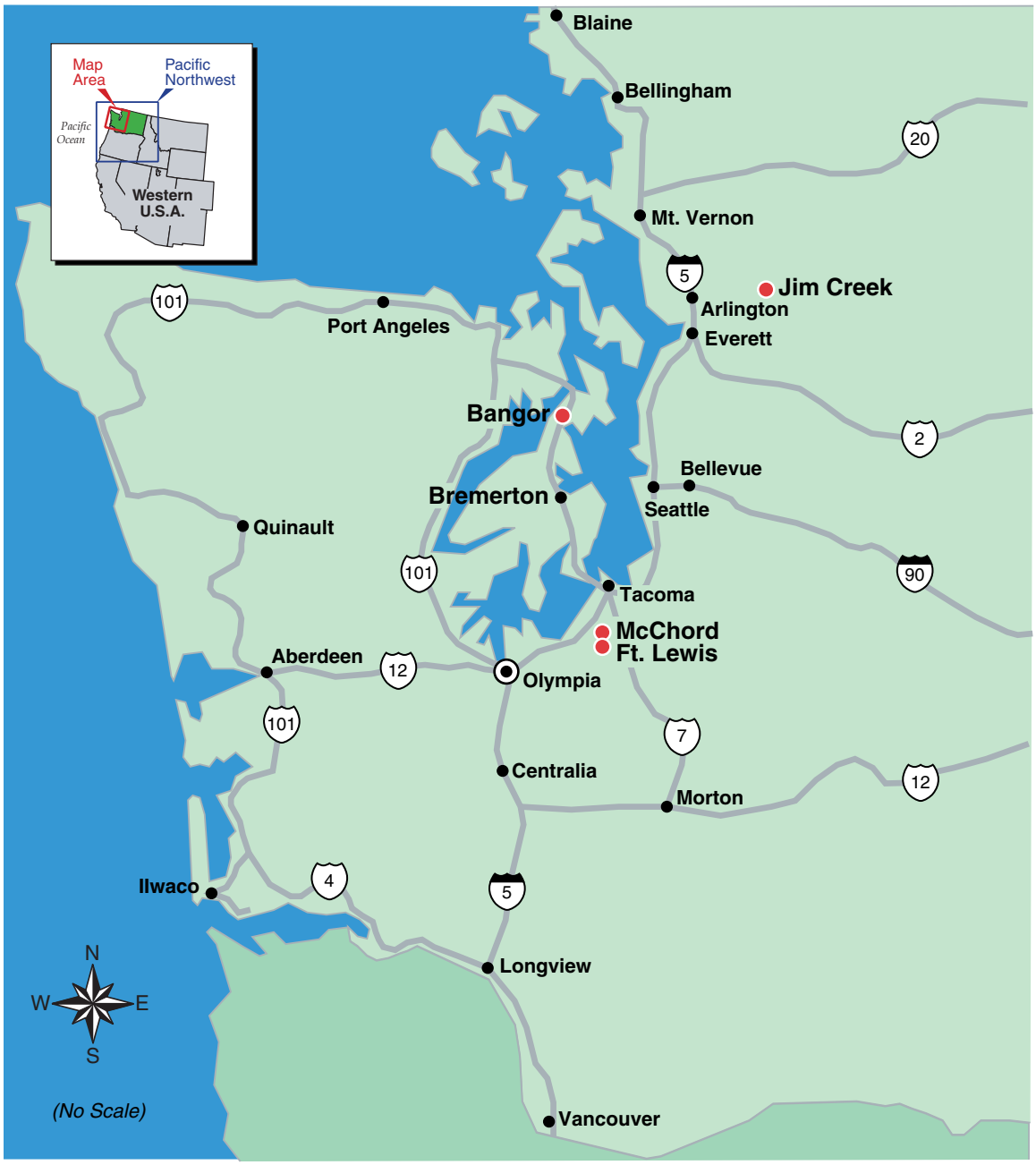

Figure 4. *Puget Sound region showing military bases.*

MILITARY-UNIQUE IMPACTS

In addition to the common impacts of development discussed in previous sections, military facilities have several unique land-use practices and military activities that can have a negative impact on aquatic resources. Some of these military-unique activities (such as military aircraft operations) have civilian equivalents (e.g., municipal airport operations), but some are only found on military installations. Examples of strictly military-unique activities include tracked vehicle (tanks and armored personnel carriers) maneuver and training areas, artillery live-fire or bombing impact areas, and explosives disposal operations. Table 2 contains a summary of all land-use activities commonly found on military facilities and their potential impact on aquatic resources.

A careful review of this table confirms that most day-to-day military operations are very similar to land-use activities found in the civilian communities that surround most military installations. This does not exempt DoD facilities from the responsibility to conserve natural resources. On the contrary, in many cases, because of the requirements for open space to safely conduct many of the military-unique activities, the level of development inside DoD facilities is often less than their surrounding communities.

Appendix A contains a more detailed breakdown of military operational and land-use activities and their potential impact on aquatic resources. This information can be utilized by natural resource managers and base commanders to plan for future operations and facility construction projects so as to minimize the potential impacts on water quality and aquatic ecosystems. This potential impact matrix is generic in scope rather than being site-specific. A discussion of individual impacts for each base assessed during this project is contained in later sections of the report. Appendix B contains the same list of potential impacts found in Appendix A, but contains the regulatory or legal reference for each potential impact. This will also aid resource mangers and base commanders in planning and implementing conservation activities in response to specific regulatory requirements (i.e., CWA, ESA, etc.). In general, military-unique impacts on aquatic resources fall into three main categories:

- Encroachment, degradation, or destruction of habitat.
- Physio-chemical water quality impairment.
- Stormwater run-off quantity and quality problems.

Table 2. *Summary of major DoD activities impacting aquatic resources in order of most frequent/significant impact.*

Activity	Type	Types of pollutants
Buildings, paved roads, parking lots, railroads, curbs, and sidewalks	NPS	Low dissolved oxygen, nutrients, sedimentation, bacteria, pathogens, chemicals, metals, pH, habitat and hydrologic modification, POL, debris, thermal
Construction and other ground-disturbing activities	NPS	Nutrients, sedimentation, habitat and hydrologic modification, POL, debris
Dams, culverts, or dredging	NPS	Low dissolved oxygen, nutrients, sedimentation, bacteria, pathogens, chemicals, metals, pH, habitat and hydrologic modification, POL, debris, thermal
NPDES permitted industrial PS discharges	PS	Low dissolved oxygen, nutrients, sedimentation, bacteria, pathogens, chemicals, metals, pH, habitat and hydrologic modification, POL, debris, thermal
NPDES storm water discharges	NPS	Low dissolved oxygen, nutrients, sedimentation, bacteria, pathogens, chemicals, metals, pH, habitat and hydrologic modification, POL, debris, thermal
Artillery or other live fire impact areas	NPS	Low dissolved oxygen, nutrients, sedimentation, bacteria, pathogens, chemicals, metals, pH, habitat and hydrologic modification, POL, debris, lead and dust emissions
Tracked vehicle training and maneuver areas	NPS	Low dissolved oxygen, nutrients, sedimentation, bacteria, pathogens, chemicals, metals, pH, habitat and hydrologic modification, POL, debris
Equipment or material storage sites (uncovered)	NPS	Chemicals, metals, pH, POL
Fixed-wing and rotary-wing aircraft maintenance	NPS	Toxic chemicals, metals, solvents, air emissions, pathogens, POL, debris
De-icing application	NPS	Chemicals, nutrients
Open burning/open detonation (OBOD) sites	NPS	Explosives, munitions, metals, solvents, other air pollutants, particulates, and explosive by-products
Ship building, maintenance and repair	NPS	Chemicals, metals, solvents, air emissions, POL, debris, pathogens
Motor pools and vehicle maintenance centers	NPS	Low dissolved oxygen, nutrients, sedimentation, bacteria, pathogens, chemicals, metals, pH, POL, debris
Fueling stations and operations	NPS	Sedimentation, chemicals, metals, pH, POL, debris
Fertilizer and herbicide application	NPS	Nutrients, chemicals
Underground storage tank leaks	PS	Chemicals, metals, pH, POL
Water supply or ground water withdrawal wells	PS	Nutrients, sedimentation, pH, chemicals

Notes: (1) PS = point-source pollution

(2) NPS = non-point-source pollution

(3) POL = petroleum oils and lubricants

Habitat destruction, degradation, or "encroachment" can be caused by permanent development within or near sensitive areas such as wetlands or stream-riparian corridors, and by transient operations within these same areas or in close proximity to them. The conservation of wetlands and stream corridors has only recently been recognized as a significant environmental imperative. As a result of historic land-use activity much of the region's natural wetlands were lost to agricultural conversion and development (*Kruckeberg*, 1991). Much of the old-growth and mature forests of the PNW were also lost due to repeated cycles of logging. This includes upland forests as well as riparian forests, especially in the PSL region (*Kruckeberg*, 1991). Unique natural habitats such as the South Puget Sound Prairie (SPSP) have also been destroyed or modified by human land-use activity in the region. This "oak-savannah" ecosystem was common in the area where Fort Lewis now exists prior to non-indigenous settlement of the region (*Kruckeberg*, 1991). Most of this ecosystem has been lost to agriculture and development over the past 200+ years (see Fort Lewis section for details).

The replacement of natural vegetation by roads, buildings, parking areas, and turf areas is the most common form of habitat alteration in the PNW. The resultant shift in hydrologic function from a sub-surface flow regime to a surface run-off dominated regime is usually the first manifestation of this landscape level change (*Booth*, 1991; *May et al*., 1997; *Roesner*, 1997; *Horner and May*, 1999; *May and Horner*, 2000; *Horner et al*., 2001). The increase in run-off volume and flood frequency that results from watershed urbanization is typically accompanied by a degradation in water quality in the form of physio-chemical pollutants. These include fine sediment from construction sites, oils and petroleum products associated with transportation infrastructure, toxic metals, pesticides, herbicides, and nutrients from a variety of land-use activities (see Table 1). Non-point source (NPS) pollution can be caused by stormwater run-off from developed areas on DoD facilities and/or military-unique operations such as tracked vehicle training exercises, artillery firing, or open-burning or open-detonation (OBOD) sites. NPS pollution can enter natural water bodies via run-off and cause water quality degradation due to physical (e.g., silt or sediment) or chemical (e.g., toxic chemicals) pathways. In addition, invasive plant and exotic animal species have displaced many native species within the region (*Kruckeberg*, 1991). All of these physical, chemical, and biologic stressors combine into the cumulative impacts we see reflected in the current condition of the region's aquatic ecosystems.

STUDY METHODS

Introduction

In accordance with the 1972 Federal Water Pollution Control Act and its amendments, collectively known as the Clean Water Act (CWA), the objective of water resource management efforts in the U.S. should be to "restore and maintain the chemical, physical, and biological integrity of the nation's waters". These three components together are commonly referred to as *ecological integrity*. Regulations promulgated by the U.S. Environmental Protection Agency (US EPA) to enforce these acts are based on the concepts of "designated beneficial uses" and "best attainable conditions." After the passage of the CWA, tremendous progress was made cleaning up polluted waters throughout the country. Point sources of pollution, such as sewage treatment plants and industrial discharges were the primary targets of the first phase of this effort. Current water pollution programs concentrate on non-point source (NPS) pollution as the primary concern. NPS pollution includes urban stormwater run-off, agricultural pollution, and other sources dispersed throughout watersheds. In addition, until recently, most surface freshwater monitoring programs focused almost entirely on chemical water quality monitoring. In spite of these efforts, the quality of the nation's aquatic resources has continued to decline (*Karr*, 1991).

A recent National Research Council report (*NRC*, 2001) stated that certain aspects of the U.S. EPA water quality standards program and the approach currently used to list impaired waters under section 303(d) of the CWA should be revised to reflect best available science. The NRC report recommended that jurisdictions be required to first develop appropriate designated beneficial uses for water bodies and then use that as a basis for logically defining the criteria to be used to measure whether the use is met. The NRC report also stated that a narrow focus on chemical water pollutants was not in keeping with the goals of the CWA or with the current level of scientific knowledge. Physical habitat conditions and other ecological factors should also be taken into account when designating and evaluating water bodies for management. Moreover, the report stated that any water resource management program should "consider biological criteria to determine whether a water body is meeting its designated uses or is impaired." The report went on to state that biological criteria tend to be more closely related to designated beneficial uses than traditional chemical water pollution criteria.

Clearly a more integrated approach to what is commonly called "water quality" monitoring is needed. This approach should include all aspects of ecological integrity (chemical, physical, and biological). This is particularly true in the Pacific Northwest (PNW) where concerns about native salmon and Endangered Species Act (ESA) listings of these valuable aquatic resources have pushed water quality issues into the forefront of environmental policy decisions. Because declining ecological conditions have many potential causes (e.g., chemical pollutants, degraded habitat structure, modified hydrologic regime, alterations in watershed landscape, and biotic interactions), a broader perspective is needed (*Karr and Chu*, 1999). Monitoring approaches that focus only on the sources of degradation (the stressors) rather than directly measuring the aquatic ecosystem conditions, including native biota and physical habitat (the response), often substantially underestimate degradation to streams and rivers (*Karr*, 1991; *Davis et al.*

1996; *Yoder and Rankin*, 1998). This holistic approach implies that the assessment of physical habitat conditions (both quantitative and qualitative) and biological integrity should be used along with the more traditional chemical water quality criteria, to determine whether designated *beneficial uses* are attainable. Recognizing this, more than 31 states have adopted some form of biological criteria into their water quality standards over the past decade (*Davis et al*., 1996). The US EPA has made it a priority that biological criteria be a key component in the water quality programs of all 50 states by the year 2005 (*US EPA*, 1998). Physical habitat monitoring has also been adopted as a standard assessment procedure in a number of regions and states. In addition, the condition of the watershed as a whole must be established to serve a landscape level context for more detailed assessment and analysis.

With regard to Pacific salmon and trout (salmonids), *habitat* consists of places where individuals, populations, and assemblages can find the physio-chemical requirements to support their life histories. At various life-stages, salmonids require different environmental features and conditions to survive and develop. These habitat features include supportive water quality conditions, migration routes, spawning habitat, rearing habitat, feeding areas, and refugia. In addition to the amount of habitat available to salmonids, habitat quality, diversity, and distribution also will influence the abundance, species composition, and general health of salmonids within a particular stream system. The general life cycle of salmonid species is shown in Figure 5. An effective salmonid habitat monitoring program must include elements that measure habitat conditions representative of each of these life-stages. In addition, the program should include monitoring parameters that measure the overall biological integrity of the stream ecosystem.

Along with CWA requirements, the recent Endangered Species Act (ESA) listing of several salmon species in the Puget Sound area makes it essential that resource stewards do a better job of managing our aquatic ecosystems. ESA requires that the resource be recovered to natural, self-sustaining levels and that *critical habitat* of the listed species be restored or protected. Stream habitat loss and/or degradation is one of the most influential limiting factors impacting salmon productivity and diversity. In fact, *habitat* is often cited as one of the so-called "4 H's" that categorize the major factors responsible for the decline of salmon populations in the PNW, the others being harvest, hatcheries, and hydro-electric/irrigation dams. These regulatory requirements are among the driving forces behind stream habitat assessment.

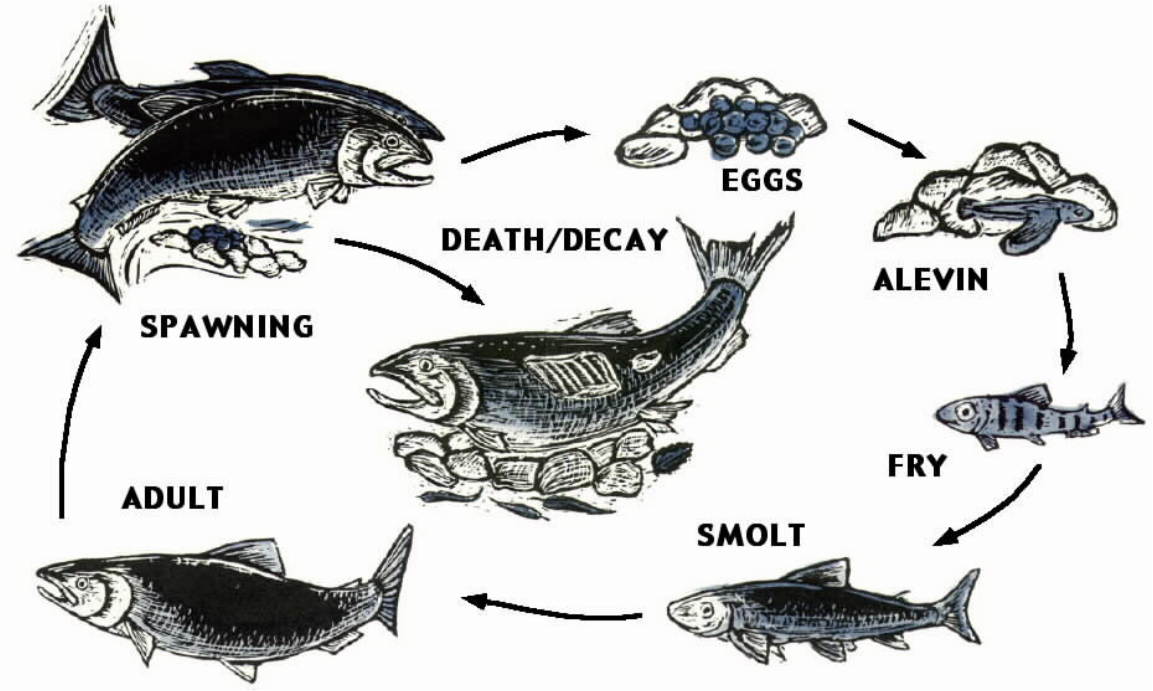

Figure 5. *Generalized salmonid life cycle*

In addition to these and other regulatory forces, *watershed-based management* programs have been recognized as the most effective way to provide stewardship for aquatic resources. Both the scientific and political communities have broadly accepted these programs as the most effective method of managing aquatic resources. Effective watershed stewardship requires the use of *adaptive management* to provide continuous feedback on and refinement of management activities. An essential element of this feedback loop is a well-designed monitoring program. It has been widely recognized that a comprehensive evaluation of watershed aquatic resources requires an integrated physical, chemical, and biological assessment program.

It should be obvious that there is a sound scientific basis for a multi-parameter (physical, chemical, and biological) approach to monitoring ecosystem quality, including the stream ecosystems that support native salmon and trout in the PNW. Natural, undisturbed ecosystems normally have a high level of ecological integrity. These ecosystems possess both the structural and functional characteristics required to support a diverse array of native biota, often referred to as *biodiversity*. In order to gain an understanding of ecosystem strengths and problems, monitoring parameters that reflect the full array of structural and functional elements are necessary. Instream physical habitat tends to be more structural in nature, but also responds to ecosystem (function) processes as well and is a critical component when evaluating aquatic ecosystems that support native salmonids.

Watershed Assessment

It is generally recognized that instream habitat conditions and water quality characteristics are a reflection of land-cover and land-use conditions within the watershed or sub-basin of the stream, lake, or wetland of interest. In an effort to characterize watershed conditions that may be contributing to habitat quality of each stream system, sub-basins were delineated and analyzed using standard watershed assessment protocols. Geographic Information System (GIS) data, aerial photographs, and other data sources can be used to determine sub-basin conditions. *Watershed assessment* is an on-going process of compiling and analyzing technical information on watershed conditions, and the effect of human activities on those conditions. It is the first step in a long-term *watershed management* program. Ultimately, watershed management, including conservation and restoration efforts, will be a key local building block in integrated regional ecosystem management efforts. Because data availability and technical resources vary across geographic areas, the way watershed assessment tasks are approached and the time frame for accomplishing them varies.

A single assessment method or tool will likely not provide all the information needed to effectively manage a watershed based on multiple beneficial uses. However, a standardized assessment framework is needed to bring together different assessment elements, improve consistency, and synthesize data for more effective watershed management. A science-based watershed assessment analyzes the past and current state of the watershed, captures its unique physical, chemical, and biological characteristics, and compares these conditions to those in natural "reference" watersheds. It should explicitly identify uncertainty of information and be supported by written records that provide a basis for decision-making. Assessments help determine how well a watershed is functioning and how it responds to natural and human disturbances. They should aid understanding of how a watershed "works" and how a watershed has changed as a result of human activities.

The key components involved with watershed assessment include the following:

1. Describe the <u>general physical, biological, and chemical attributes of the watershed</u> (i.e., geology, climate, topography, hydrology, and soil structure). Watershed characterization is the description of the current natural and human-related attributes of the basin and includes:
    - Dominant natural and human features of the watershed that affect ecosystem function and biological integrity.
    - Cataloged and/or mapped watershed attributes such as geologic, soil, and topographic characteristics.
    - Key land-use features and land-cover patterns, including roads, forested areas, and development levels, usually on a map.
    - Municipal jurisdictions and regulatory responsibilities within each watershed.
    - Current and historic salmonid utilization for each stream system.

- A list of beneficial uses common to the watershed and their relative importance.
- Unique or critical resource issues and problems.
- Water-resource management programs that currently exist.

2. Identify and describe factors within the watershed, both natural and human-caused, that affect the physical, biological, and chemical attributes of the watershed. This includes analysis of:
    - Hydrologic conditions - low flows, peak flows, water use, land cover, land-use, and impervious surfaces.
    - Soil erosion and sediment load and sources – roads, construction sites, landslides.
    - Natural vegetation patterns and characteristics – riparian corridors, upland forests, and other native vegetation.
    - Wetland, floodplain, and nearshore/estuary conditions within or adjacent to the watershed.
    - Biological communities – aquatic and terrestrial biota.
    - Water quality conditions – chemical characteristics and pollutants of concern.
3. Identify and describe human-caused factors existing outside of the watershed that affect the physical, biological, and chemical attributes of the watershed; (e.g., an upstream dam that regulates flow or modifies water temperature, a source of chemical pollution or turbidity, or degraded aquatic habitat).
4. Classify and subdivide the watershed into sub-watersheds to facilitate comparative assessment of existing conditions and prioritization of management prescriptions.
5. Identify data gaps that need to be filled to reduce uncertainty in the development of recommendations to address problems.

Modifications of the natural landscape during the development process can produce tremendous changes in the patterns and the processes of the watershed, especially in the hydrologic regime. These changes result from clearing vegetation, compacting soil, ditching and draining, and finally covering the land surface with impervious rooftops and roads. The infiltration capacity of these impervious areas is significantly reduced, and much of the remaining soil-covered area may also be compacted to a near-impervious state (lawns, golf course, sports fields, etc.). Compacted soil and other impervious surfaces also tend to have lower storage volumes, and so even if precipitation can infiltrate, the soil reaches surface saturation more rapidly and more frequently, resulting in more run-off and more frequent flood events. These cumulative impacts result in pervasive changes to water quantity, water quality, and the associated ecological function of streams, wetlands, and riparian ecosystems. In addition to changes in how rainfall is absorbed or runs off of watershed upland hillslopes, land development affects other

elements of the drainage system. Roadside ditches, gutters, storm drains, and storm sewers are laid in the urbanized area to convey run-off rapidly from roads and developed properties to stream channels. This results in a significant increase in *drainage-density* of the watershed, further altering the natural hydrologic regime. In addition, natural channels are often straightened, deepened, or lined with concrete to make them hydraulically more suited to conveying stormwater. Each of these changes increases the efficiency of the channel, transmitting the stormwater run-off downstream faster and with less interaction with the channel. This results in less energy dissipation by natural channel features and more erosive stream power acting on the channel. The end result is that the stream channel gradually unravels and instream habitat is destroyed or degraded to the extent that it will no longer support native stream biota.

Watershed development or urbanization is one of the most significant threats to the ecological health of streams and rivers in the Puget Sound lowland (PSL) region (*May et al*., 1997). The trend is similar across the rest of the United States. Urban and suburban development now covers about 20% of the country, with over 75% of the population living in those areas (*Stoel*, 1999). This is a major shift away from the rural lifestyle of Americans during most of the 20th century. Between 1970 and 1990, rural lands were converted to residential and commercial centers at the rate of 400,000 acres per year (*American Rivers*, 1999). As the landscape changes from forests and fields to one dominated by roads, parking lots, lawns, and rooftops (e.g., impervious surfaces), natural ecosystems become increasingly threatened, sometimes disappearing completely. This is certainly true of our freshwater aquatic ecosystems. The impacts of watershed urbanization across the U.S. have been well documented (*Leopold*, 1968; *Hammer*, 1972; *Hollis*, 1975; *Klein*, 1979; *Arnold et al*., 1982; *Booth*, 1991; *Schueler*, 1995). They include extensive changes in basin hydrologic regime, channel morphology, and physiochemical water quality. The cumulative effect of these alterations has produced an instream habitat that is significantly different from that in which salmonids and associated fauna have evolved. In addition, development pressure has a negative impact on riparian forests and wetlands, which are essential to natural stream functioning.

Considerable evidence of these effects exists from many studies of urban streams in the PSL region (*Perkins*, 1982; *Richey*, 1982; *Steward*, 1983; *Scott et al*., 1986; *Booth*, 1990; *Booth and Reinelt*, 1993; *Taylor*, 1993; *May et al*., 1997; *Morley*, 2000). The cumulative effects of watershed urbanization in the PSL region have resulted in a loss of natural forest and wetland cover, as well as a significant increase in impervious surface area. Riparian forests, floodplains, and off-channel wetlands have also been severely degraded by the incremental encroachment of residential and commercial development. The decline in ecological integrity of the stream-riparian ecosystem appears to begin at very low levels of watershed development and continues with increasing watershed urbanization.

Between 1970 and 1990, the population of the Puget Sound region increased by almost 40%, accompanied by 90% increase in land development during the same time period (*American Rivers*, 1999). Much of this development activity tends to be concentrated along stream and river corridors (*Omernik and Gallant*, 1986). Streams are highly connected to the landscapes they drain (*Naiman and DeCamps*, 1990; *Vannote et al*., 1980; *Ward*, 1989). The shift in the watershed land-cover of the PNW from a forested

landscape to a mosaic of developed land uses has had a profound effect on the aquatic ecosystems of the region. For example, alteration of stream flow regime, which affects biota through a range of direct and indirect effects on physical channel conditions (*Poff et al*., 1997), is generally a function of basin-wide processes (*Allan et al*., 1997, *Hunsaker and Levine*, 1995; *Roth et al*., 1996; *Richards and Host*, 1994; *Richards et al*., 1996; *Roesner*, 1997; *Steedman*, 1988; *Wang et al*., 1997; *Morley*, 2000). In the pre-development forested condition, the abundant but low-intensity rainfall characteristic of this region was conveyed to streams almost entirely as sub-surface flow. In urbanized basins now covered largely by impervious surfaces, a shift from sub-surface to overland flow has significantly altered the delivery of water and sediment to the stream channel (*Booth*, 1996; *Booth and Jackson*, 1997; *Dunne and Leopold*, 1978; Horner and May, 1999). The flow regime of developed basins commonly displays an increase in magnitude, duration, and frequency of peak winter flow, and may also show a marked decrease in summer baseflow (*Booth and Jackson*, 1997; *Hollis*, 1975; *Richter et al*., 1996). Increased run-off also provides greater opportunity for sediment delivery to the channel, especially when there is land clearing, construction, or agricultural activity in the basin. Local scale effects, often influenced by streamside soil and plant cover and local land use practices, include streambank erosion, channelization, streambank hardening, streamside vegetation loss, and use of toxic chemicals.

Because of this profound effect of watershed development on aquatic systems, characterizing the land cover of a region is critical for a variety of resource management related reasons. In the PNW, this characterization has been used most commonly to correlate the intensity of human activity with observed stream or wetland conditions, in order to predict the health of the stream system or to guide the allocation of mitigation efforts. For example, measured ecological conditions in lowland streams are regularly presented in terms of the total impervious area percentage (% TIA) of the contributing watershed. Land cover is also a primary input parameter for numerical hydrologic models that are widely used by the storm/surface-water management (SWM) agencies of the region. Unfortunately, there is little consistency or quality control in how land-cover or land-use data are collected and analyzed.

The characterization of land cover for purposes of evaluating and assessing watershed conditions is one of the most common applications. Typically, this has been done using aerial photographic analysis. Recently, remotely sensed data from satellites has been used to provide an alternative land-cover data source. The traditional approach to classifying remotely sensed data from satellites into discrete classes of land-cover involves a lengthy process of automated classification, clustering of spectral signatures, much fine-tuning, and an eventual supervised classification (*Hill et al*., 2000). This process can be both time and resource-intensive. It is also continually being refined, and so the methodologies are again not consistent. The University of Washington Center for Urban Water Resources Management (UW-CUWRM) has developed an alternative approach using "Land-Sat" satellite imagery to produce the same general type of land-cover characterization as has currently found widespread acceptance and use across the region. This methodology does so in a way that achieves maximum utility and consistency for individuals and agencies needing to assess watershed conditions in developed or developing areas of the PSL eco-region (*Hill et al*., 2000). The classes of land cover produced have been chosen to reflect the categories that can be readily distinguished in

the satellite data and to have important differences in their associated run-off and watershed characteristics (see Tables 3 and 4). The advantages of such an approach are obvious. The algorithm is developed only once; after completion, it can be applied rapidly to any other selected area through GIS software. It does not depend on the discretion of individual operators and so the results are reproducible (*Hill et al*., 2000).

Although multiple land-cover categories have great utility, there is particular appeal in a single "index" variable, such as total impervious area (% TIA), which characterizes the magnitude of urban development in a watershed. Patterns can be readily displayed, correlations are simplified, and communications between scientists and decision-makers are enhanced. However, development comes in many patterns, occurs on many different types of landscapes, and is accompanied by a variety of best management practices designed to mitigate its negative effects on aquatic resources. Therefore, any simple correlation between any single measure of urbanization and aquatic-system condition is unlikely to tell the whole story. Past efforts to quantify the degree of urban development have not always been consistent, but have focused on using % TIA as the overall measure of watershed development (*Schueler*, 1995). Other studies, especially those involving hydrologic modeling typically use "effective" rather than total impervious area.

Table 3. *Land-cover categories and criteria (UW-CUWRM)*

Land-Cover	**Water**	**Forest**	**Grass**	**Bare**	**Paved**	**%TIA**
Forested Urban		>25%			20-60%	38%
Grassed Urban		<25%	>25%		<60%	74%
Paved Urban					>60%	92%
Water	>80%				<20%	0%
Bare Soil			<20%	>75%		98%
Grass/Shrub/Crops			>50%		<20%	5%
Forested		>70%			<20%	3%

% TIA = % Total Impervious Area

There is a significant distinction between *total impervious area* (% TIA) and *effective impervious area* (% EIA). Basically, % TIA is the intuitive definition of imperviousness: that fraction of the watershed covered by constructed, non-infiltrating hard surfaces such as concrete, asphalt, and buildings. This measure (% TIA) may also include nominally pervious surfaces that are sufficiently compacted or otherwise so low in permeability that the rate of run-off is similar or indistinguishable from pavement. Research in the PNW (*Wigmosta et al*., 1994) found that the impervious unit-area run-off was only 20% greater than that from pervious areas, primarily thin sod lawns over glacial till, in a western Washington residential subdivision. However, the production of significant run-off from

nominally pervious surfaces is often ignored in the characterization of urban development. The reason for such an approach lies in the difficulty in identifying such areas and estimating their contribution, although site-specific studies demonstrate that these tasks can be accomplished with simple field methods and the resulting hydrologic insights are often valuable (*Burges et al*., 1989).

The main hydrologic limitation of % TIA is that it includes some paved surfaces that may not contribute run-off to the storm run-off response of the downstream channel because they are not "connected" to the natural drainage system by a conveyance route. Some impervious areas may also be located or designed such that run-off is dispersed into areas that allow for natural infiltration. Furthermore, the degree to which pervious areas disperse run-off as overland flow should be related to the overall amount of impervious area within the sub-basin. Where construction and development is more intense and covers progressively greater fractions of the watershed, the more likely that the intervening green spaces have been stripped and compacted during construction and only imperfectly rehabilitated for their hydrologic functions during subsequent "landscaping" operations.

Effective impervious areas are defined as those impervious surfaces with direct hydraulic connection to the downstream drainage network. Thus any part of the total imperviousness that drains onto pervious or naturally vegetated areas is excluded from the measurement of % EIA. This parameter, at least conceptually, captures the hydrologic significance of imperviousness. Effective impervious area is the parameter normally used to characterize urban development in hydrologic models. However, the direct measurement of % EIA is complicated by the array of conveyance pathways typically found in developed watersheds. Studies designed specifically to quantify this parameter must make direct, independent measurements of both % TIA and % EIA (*Alley and Veenhuis*, 1983; *Laenen*, 1983; *Prysch and Ebbert*, 1986). The results can then be generalized either as a correlation between the two parameters or as a typical value for a given land use. *Dinicola* (1989) compiled the findings of the earlier studies to recommend a single set of impervious-area values based on five land-use categories for use in Puget Sound lowland watersheds. Because this analysis is being conducted at a much finer scale (Land Sat data at a resolution of 30-m pixels) and detects only land-cover differences, only % TIA is evaluated. Land-use categories, and thus EIA, might be inferred from larger clusters and patterns of individual pixels, but this lies outside the scope of this project and is not necessary for the purposes of this study.

Table 4. *Watershed assessment source data*

Basin Parameter	Source	Comments
Basin Area	7.5 minute USGS digital quad-maps and GIS digital elevation model (DEM).	The area of the watershed draining into the downstream most point of the stream-segment.
Stream Channel	Washington Department of Natural Resources (DNR) GIS Hydro layers.	Includes perennial and seasonal stream channels.
Native Forest Vegetation	Classification of Land-Sat Data.	Includes coniferous, deciduous, and mixed forest land-cover.
Bare Soil	Classification of Land-Sat Data.	Includes exposed soils from agricultural and construction activities.
Native Grassland Vegetation	Classification of Land-Sat Data.	Includes prairie grasses, open fields, and turf areas.
Urban Forest	Classification of Land-Sat Data.	Includes developed areas with trees as the dominant vegetation.
Urban Grass	Classification of Land-Sat Data.	Includes developed areas with grass as the dominant vegetation.
Urban Paved	Classification of Land-Sat Data.	Includes highways, roads, parking lots, and sidewalks.
Total Impervious Area (%TIA)	Classification of Land-Sat Data.	Using standard Puget Sound regional parameters.
Road Length (km) & Road density (km/km^2)	Washington Department of Natural Resources (DNR) GIS Road layers.	Includes all paved and un-paved roads within each sub-basin.
Road crossings (#/km)	Ortho-Photographs.	Calculated from visual analysis of orthographic aerial photographs of the streams.

Biological Monitoring

In spite of significant improvements in water quality over the last 30 years, the biological integrity of freshwater ecosystems in this country is at risk (*Karr*, 1991; *Karr and Chu*, 1999). Human modification of the natural landscape by agriculture, mining, logging, and urbanization is a principal threat to stream health in North America and across the globe (*Allan and Flecker*, 1993). Thirty-six percent of river miles surveyed for the 1994 National Water Quality Inventory failed to support healthy aquatic communities (*U.S. EPA*, 1995) and a recent study found that temperate freshwater species extinction rates are as high as for tropical rain forests (*Ricciardi and Rasmussen*, 1999). In North America, 67% of native mussels, 51% of crayfish, 40% of amphibians, and 37% of fish species are extinct or imperiled (*Master et al.*, 1998). In the PNW, native salmonid species are in sharp decline, with several stocks already extinct (*Nehlsen et al.*, 1991; *NRC*, 1996; *Lichatowich*, 2001).

Failure to demonstrate conservation and protection of water quality based on traditional monitoring methods has prompted alternative directions for evaluating aquatic resources. The continued decline in diversity of aquatic species throughout North America attests to the urgency with which conservation of water resources must be addressed (*Karr*, 1991). Traditional measurements of chemical and physical components of natural waters do not typically provide sufficient information to detect or resolve all water resource impairment problems. Biological evaluation of surface waters provides a broader approach because degradation of sensitive ecosystem processes is more frequently identified by the response of native biota to anthropogenic influences. Biological assessments supplement chemical and physical evaluation by:

- Directly measuring what are usually the most sensitive resources at risk.
- Measuring an ecological component that integrates and reflects the cumulative effects of human influence over the long-term.
- Providing a diagnostic tool that synthesizes chemical, physical, and biological perturbations within the aquatic ecosystem.

Biological integrity is defined as "a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region." *Karr* (1991) examined some of the reasons why evaluation of aquatic resources has taken so long in employing biological information. He also provided examples of how biological assessment can be applied in environmental evaluation and how powerful a tool this method is. Inclusion of multiple levels of biological measures (e.g., community trophic structure, functional feeding groups, reproductive strategy, etc.) enhances the ability for accurately diagnosing the source of degradation.

In general, biological monitoring, as an integral component of a comprehensive watershed assessment program, has the following goals:

- To define and document baseline conditions of aquatic ecosystems.
- To measure spatial and temporal variability of population and community attributes of native biota.
- To relate watershed modifications caused by human land uses (timber harvest, agriculture, and urbanization) to changes in the aquatic ecosystem biota.

Benthic Index of Biological Integrity

Over the last century, biological monitoring tools needed to establish water quality criteria have taken a number of different approaches and examined a wide range of biota, most commonly fish, macroinvertebrates, and algae. Biological assessment (measuring and evaluating biota directly) has ranged from simple diversity indexes (*Hilsenhoff* 1982), to complex toxicity testing (*Buikema and Voshell*, 1993), use of indicator species (*Farwell et al*., 1996), and more recently to multivariate models (*Parsons and Norris*, 1996; *Wright et al*., 1993) or multi-metric indexes (*Plafkin, et al*., 1989; *Karr*, 1991; *Karr and Chu*, 1999). One of the most common approaches today is the multi-metric biological index, currently in use in over 42 U.S. states and numerous countries (*Karr and Chu*, 1999). A multi-metric approach evaluates biological condition by integrating

measures of an empirically tested set of biological attributes. This approach was first used with stream fish and has since been modified for a variety of regions and taxa. One of the many advantages of the multi-metric approach is its relative simplicity; results are easily communicated and understood by non-scientists. This is a very important consideration in aquatic resource management, which is shaped as much by current policy and public opinion as by scientific study (*Morley*, 2000).

The specific method of biological assessment recommended for use in the Puget Sound lowland eco-region is the benthic index of biological integrity (B-IBI), a multi-metric index based on attributes of the benthic macroinvertebrate community (*Kerans and Karr*, 1994; *Kleindl*, 1995; *Fore et al*., 1996; *U.S. EPA*, 1996; *Karr and Chu*, 1999; *Morley*, 2000). This method of biological monitoring is widely accepted in the PNW as well as many other regions of North America.

Since the middle 1990s, scientists, water resource managers, and community volunteers have used the B-IBI to evaluate the biological condition of PSL streams and watersheds (*Kleindl*, 1995; *Fore et al*., 1996; *King County*, 1996; *May et al*., 1997; *Horner and May*, 1999; *Karr and Chu*, 1999; *Morley*, 2000). Benthic dwelling macroinvertebrates are particularly well suited for biological monitoring. They are relatively sedentary and non-migratory, usually diverse and abundant, many are sensitive to human disturbance, most are long-lived, and they are very good indicators of stream condition in that they are key components of the aquatic food-web (*Vannote et al*., 1980; *Rosenberg and Resh*, 1993; *Karr and Chu*, 1999).

The distribution of benthic invertebrates is strongly shaped by a number of factors, including adaptation to the natural flow regime, substrate size preference, food type and availability, and water temperature (*Poff and Ward*, 1989; *Statzner and Higler*, 1986; *Allan*, 1995). Alterations in the hydrologic regime are typically correlated with landscape modifications on a watershed scale (*May et al*., 1997; *Horner and May*, 1999; *Morley*, 2000). Changes in allochthonous food sources and stream shading are associated with land cover modification at the riparian scale (*Gregory et al*., 1991). In addition, local conditions, such as eroding stream banks, pollutant sources, and stream channel modifications have an impact on the macroinvertebrate assemblage (*Morley*, 2000).

Macroinvertebrate communities also tend to have greater diversity than fish communities (especially true of salmon) in the same stream, which makes evaluation with community diversity metrics more meaningful. Also, sport fishing, stocking of hatchery fish, and the introduction of exotic species often compromises the natural biological integrity of fish communities. In the case of salmon, the fish are only in the stream during specific periods of the year and so may not be exposed to the full suite of disturbances.

The B-IBI is composed of ten metrics of taxa richness and diversity, population attributes, disturbance tolerance, and feeding and other habits (see Table 5). For a given invertebrate attribute to be included as a metric in the B-IBI, it must respond predictably along a gradient of anthropogenic disturbance (*Kerans and Karr*, 1994; *Fore et al*., 1996; *Karr and Chu*, 1999; *Morley*, 2000). This dose-response relationship was tested during initial B-IBI development in the Puget Sound region (*Kleindl*, 1995) and has been replicated in subsequent years of study (*Rossano*, 1995; *Fore et al*., 1996; *May et al*., 1997; *Dewberry et al*., 1999; *Horner and May*, 1999; *Karr and Chu*, 1999; *Morley*, 2000;

Horner and May, 2001). When values from the ten metrics are combined, B-IBI ranges from a minimum of 10 to a maximum of 50 (see Table 4).

Benthic macroinvertebrates should be collected from each site between late September and early October when flows are typically stable, taxa richness is high, and field crews have easy access to stream sites without conflict with spawning salmon (*Fore et al*., 1996). At each site, a Surber sampler (500-µm mesh, 0.1-m^2 frame) should be used to collect three replicate samples along the mid-line of a single riffle. In the field, each sample will be strained through a 500-µm sieve, mineral material picked through and discarded, and the remaining sample preserved in a solution of 70% ethanol. Physio-chemical water quality data should also be recorded at each site in order to detect any significant differences in physical and chemical properties between sites, which can affect macroinvertebrate populations. The location of each monitoring site should also be mapped with a Global Positioning System (GPS) unit. The GPS data is then digitally transferred to the Geographical Information Systems (GIS). Digital pictures should also be taken and cataloged for each sample site.

The samples were then shipped to a certified biological laboratory for processing. Under microscopy, invertebrates were separated from remaining mineral and organic debris, identified, and counted. In this manner, each sample was processed and identified separately without compositing or sub-sampling (*Karr and Chu*, 1999). Insect nymphs and larvae, the bulk of benthic samples, were identified to genus where practical; non-insect taxonomic identification varied from family to phylum. Non-benthic invertebrates, pupae, and terrestrial adults were excluded from sample analysis. A complete reference set of invertebrates identified throughout the study was also assembled and verified by independent analysis.

The selection criteria for biological sample sites included locating sites so as to best represent the conditions found in each sub-watershed or stream segment of interest. Some of the selected sites may have permanent streamflow and water quality (WQ) monitoring stations already established. In these situations, the bio-monitoring sites can then be collocated with these established monitoring stations and data can be cross-referenced. In other cases, selected tributary streams of special interest may be selected based on unique sub-basin land-use characteristics or because of the ecological significance of particular streams segments. In general, the sampling sites should be located throughout all watersheds to get the best possible representation of natural and anthropogenic influences to the streams.

In previous studies in the PSL eco-region, several bio-monitoring sites have been identified as *reference sites*. These sites are located in undeveloped watersheds. These watersheds have minimal human influence and act as natural "control sites" to compare with sites located in the watersheds more affected by anthropogenic influence. Reference conditions are especially important in developing biologically meaningful criteria to protect aquatic resources (*Hughes et al*., 1986). The reference condition reflects biological community potential in an ecosystem, and is also used to describe spatial and temporal trends. But to be effective, reference sites should reflect the variety of natural conditions that occur within a set of similar stream types (*Reynoldson et al*., 1997). This is best achieved through long-term monitoring of reference as well as degraded sites. Long-term (multiple year) data are critical for providing measures that will describe

typical inter-annual variability and better define natural, reference conditions. Environmental conditions such as climate or the natural disturbance cycle vary between years and subsequently influence stream biological communities. A key step in differentiating natural environmental influences from anthropogenic influences is to measure inter-annual variability, thus long-term biological monitoring is a must for effective watershed management.

Table 5. *Metrics of the PNW B-IBI and their predicted and observed response to watershed development (*Karr and Chu*, 1999)*

B-IBI Metric	**B-IBI Category**	**Ecological Response**	**Scoring Criteria**		
			1	**3**	**5**
Total Taxa (#)	Richness	Overall biodiversity decreases as aquatic ecosystem is altered	0-19	20-40	>40
Mayfly (*Ephemeroptera*)	Richness	Diversity of Mayflies generally declines with human influences. Particularly sensitive to chemical pollutants and changes in nutrients or food sources.	0-4	5-8	>8
Stonefly (*Pleoptera*)	Richness	Some of the most sensitive organisms. Very sensitive to sedimentation of substrata and to higher stream temperature.	0-3	4-7	>7
Caddis-fly (*Tricroptera*)	Richness	Diversity declines steadily with human influences, especially hydrologic changes	0-4	4-9	>=10
Long-Lived Taxa	Richness	Live in stream for more than 1 year. Sensitive to human influences that change annual cycles such as hydrologic regime	0-2	3-4	>4
Dominance of the 3 most common Taxa (%)	Relative Abundance	As biodiversity declines with human influence, a few taxa tend to dominate the macroinvertebrate assemblage. Opportunistic species tend to increase.	>75%	50-75%	<50%
Sensitive Taxa	Richness	Intolerant taxa are the first to disappear with human influence	0-2	3	>3
Tolerant Taxa (%)	Relative Abundance	Tolerant taxa are always present, but as human disturbance increases, these organisms begin to dominate the macroinvertebrate assemblage.	>50%	20-50%	<20%
Clinger Taxa	Richness	These organisms live on the streambed substrata. Very sensitive to siltation and flow increases resulting from human land-use activities.	0-10	11-20	>20
Predators (%)	Relative Abundance	Represent the top of the benthic macroinvertebrate food-web. Depend on abundance and diversity of other macroinvertebrate organisms. Less disturbed sites tend to support a greater diversity of prey and thus have more predators.	0-10%	10-20%	>20%

Table 6. *Five classes of biological condition in the B-IBI (*Morley*, 2000)*

Biological Condition	B-IBI Score	Description
Excellent	46-50	Comparable to least disturbed reference condition; overall high taxa diversity, particularly of mayflies, stoneflies, caddis-flies, long-lived, clinger, and intolerant taxa. Relative abundance of predators high.
Good	38-44	Slightly divergent from least disturbed condition; absence of some long-lived and intolerant taxa; slight decline in richness of mayflies, stoneflies, and caddis-flies; proportion of tolerant taxa increases.
Fair	28-36	Total taxa richness reduced - particularly intolerant, long-lived, stoneflies, and clinger taxa. Relative abundance of predators declines; proportion of tolerant taxa continues to increase.
Poor	18-26	Overall taxa diversity depressed; proportion of predators greatly reduced as is long-lived taxa richness; few stoneflies or intolerant taxa present; dominance by three most abundant taxa often very high.
Very Poor	10-16	Overall taxa diversity very low and dominated by a few highly tolerant taxa; mayfly, stonefly, caddis-fly, clinger, long-lived and intolerant taxa largely absent. Relative abundance of predators very low.

Fish Surveys

Although the B-IBI is recommended as the primary method of bio-monitoring there is sound reasoning for actually monitoring salmonids during their various life-stages. Long-term records of salmon abundance diversity from each watershed would be a valuable source of data for making management decisions. A variety of methods can be used to determine salmonid distribution, abundance, and/or diversity within a stream system. Tribal and WDFW biologists should be consulted prior to implementing any of these survey techniques. The following are the most widely recognized methods of monitoring salmonid utilization within a stream system:

1. Spawning Surveys – Periodic counts of adult salmon spawning and/or counts of spawned-out carcasses. Tribal biologists utilized this method to calculate "escapement."
2. Adult Migration Surveys – Periodic counts of adult salmonids moving upstream to spawn. Usually done at fixed weir or stream crossing where observation is easy.
3. Juvenile Trapping – Smolt trapping is the most commonly used method of counting juvenile salmonids. This is done by temporarily blocking the stream

channel during the out-migration of juveniles and counting the smolts prior to releasing them downstream. Another more qualitative method uses standard "minnow-traps" to sample juvenile salmonids within a stream reach.

4. Snorkeling – This method can be used to count adults or juveniles and is best suited for rivers or larger streams. The American Fisheries Society is currently developing a standard protocol for this method.
5. Electro-fishing – This method was once the standard practice used to estimating juvenile abundance and diversity. However, recent studies have indicated that the mortality from "electro-shocking" is much higher than previously thought. Based on these findings, this method is not recommended for future use.

Physio-Chemical Water Quality

To ensure long-term survival and persistence, salmon and trout require cold, clean water as part of their habitat. There are numerous physio-chemical water-quality (WQ) variables that could be monitored, but there are only a few that have ecological significance for salmonid habitat. These include the parameters listed below plus nutrients and toxic chemicals. As a whole, there are still fewer WQ parameters that can be easily and reliably measured in the field. The WQ parameters that should be monitored routinely include the following:

- Temperature (T)
- Dissolved oxygen (DO)
- pH (pH)
- Conductivity (C)
- Total suspended solids (TSS) or turbidity
- Discharge or streamflow (Q)

Temperature is a critical habitat variable for cold-water fish such as salmonids. Under natural conditions, the streams of the PNW are kept cool throughout the year due mainly to their well-shaded conditions maintained by a forested riparian corridor. In addition, groundwater and wetland recharge of streams also helps to maintain cool water temperatures, even during the warm summer months. An increase in stream temperature can increase the metabolic activity of aquatic organisms and may alter their behavioral patterns. A small increase in water temperature may have a short-term positive influence on stream organisms, but higher than normal stream temperatures may also have long-term negative impacts. Currently Washington WQ criteria require daily-maximum stream temperatures to be maintained below a specific level to support properly functioning salmonid habitat conditions. The recommended criteria are designed to protect the key life-stages of adult holding, spawning and incubation, juvenile rearing, smoltification, and adult migration. The criteria have also been set to avoid significant increases in the risks of warm water fish diseases and parasites. In reality, each salmonid species has a slightly different "preferred" or "optimal" temperature range for each life-stage, which makes establishing appropriate WQ criteria very problematic. In general, the optimal temperature range for most salmonid species and life-stages is approximately 12–14˚C.

Therefore, if observed temperatures are consistently greater than 16˚C, there is likely a problem, which should be investigated. Likely causes of high instream temperature include a loss of riparian shade, inputs of warm wastewater, and lack of adequate flow due to impoundments (dams) or water withdrawal for human consumption or irrigation. Temperature should be measured only with a calibrated thermometer.

Dissolved oxygen (DO) is another critical WQ parameter to ensure a PFC for salmonid habitat. DO refers to the quantity of oxygen dissolved in the water and available to aquatic organisms for respiration and metabolism. The capacity of water to hold oxygen is inversely proportional to the water temperature. When DO is at saturation it means that it is at equilibrium with the atmosphere and no more oxygen can be dissolved in the water at that temperature. Oxygen is dissolved in water through contact with the air and aeration caused by turbulent flow. The actual DO concentration (mg/l) in water depends not only on temperature (saturation concentration), but also on DO sinks or sources. The primary DO sinks are biotic respiration and decomposition of organic matter, commonly referred to as biochemical oxygen demand (BOD). The primary DO sources include photosynthesis by aquatic vegetation and the aeration process discussed above. DO is closely linked to temperature because as temperature rises, saturation concentration is depressed and BOD increases. In general, natural streams in the PNW have cool temperatures, high aeration rates, and relatively low BOD levels; thus instream DO is normally at or very close to saturation. This is the optimal habitat condition for native salmonids as well. Streams in low gradient areas that have low streamflow, streams that lack riparian shade, and those with high levels of organic matter (or wastewater) that result in high BOD levels, are more likely to have problems with low DO. Current Washington WQ criteria call for DO to be maintained above 8 mg/l. Salmonids may become impaired if DO goes below 6 mg/l for extended periods and lack of DO can be lethal at levels less than 3 mg/l. In general, DO should be maintained as close to saturation as possible for optimal, long-term salmonid habitat. Instream DO can be measured using a calibrated DO meter or by the "Winkler" method using an approved chemical test kit. A DO level that is consistently significantly below saturation level (or <6 mg/l) for the temperature should be investigated for possible sources of BOD.

The DO concentrations can vary between the surface of the water column and at depth due to a variety of environmental influences, including temperature, BOD, and biotic interactions. The DO available to benthic organisms and salmonid eggs/embryos can also vary depending on the amount of fine sediment or "silt" deposited on and in the streambed substrate. This is commonly referred to as intergravel DO (IGDO). This is very important to the survival of salmonids during their embryonic or alevin life-stage. Oxygen replenishment of the intergravel habitat comes primarily from the exchange of well-aerated surface water known as *hyporheic* flow. IGDO concentration depends on many of the same factors as surface water, but is also controlled by the streambed permeability. Excessive levels of fine sediment or "fines" will hinder hyporheic flow and can result in increased salmonid egg-embryo mortality or reduced growth and development of alevins. IGDO measurements can be used as a surrogate for the amount of interstitial fines and as an indicator of streambed spawning-gravel quality. Salmonids can greatly modify spawning gravel conditions, particularly the amount of interstitial fine sediment, through the redd-building process. In fact, it is generally thought that large numbers of spawning salmon, such as are common in areas not impacted by human

activity, are capable of "cleaning" the streambed of fine sediment during spawning periods. Therefore, IGDO monitoring sites must be carefully selected to represent actual intergravel DO conditions that salmonid eggs-embryos will experience.

pH is a measure of the alkalinity or acidity of the water. pH is dependent on temperature and chemical composition of the water. Based on the alkalinity or acidity of the water, pH is an indirect measure of the "buffering" capacity of the water or its ability to neutralize acids and bases. In order to fully measure the acid neutralizing capacity of water, alkalinity must also be measured. The most important buffering agent in freshwater is carbon dioxide (CO_2). pH can have direct and indirect effects on instream water chemistry and on aquatic biota. Low (acidic) pH conditions can reduce salmonid egg production, decrease embryonic development, and delay alevin emergence. pH can also influence the "speciation" of other chemicals found in the water. Metals and other chemicals can shift from particulate form to dissolved form and back as pH and temperature changes. Based on this, the toxicity of specific chemicals can change as pH changes. pH should be between 6.5 and 8.5 in order to support optimal salmonid habitat conditions.

Conductivity (or specific conductance) is a measure of the quantity of dissolved ionic material in water. It can also be an indirect measure of salinity and total dissolved solids (TDS). Conductivity is measured with a calibrated conductivity meter. It is easy to measure in the field and is very useful as an early-warning WQ tool. Research has indicated that as non-point source (NPS) pollution and stormwater run-off increases, the amount of dissolved ionic material also increases, as does conductivity. Streams draining forested watersheds in the PNW normally have a conductivity well below 100 µmhos/cm. Streams draining more urbanized watersheds are likely to be greater than 100 µmhos/cm, especially if there are significant sources of water pollution present. A significant increase in conductivity, an increasing trend, or an unusually high reading should trigger additional water chemistry analyses (nutrients, metals, organics, etc.) and an investigation for possible sources of pollution.

Turbidity or total suspended solids is a measure of the amount of particulate material in water. The amount of suspended sediment in a stream will depend primarily on the particle size distribution of sediment and the streamflow. The quantity of fine sediment carried by a stream has several potentially significant impacts on ecological integrity. As was discussed earlier, fine sediment that is deposited in streambed spawning gravel can impact the early life-stages of salmonids. Nutrients and potentially toxic chemicals can also be adsorbed onto fine sediment particles. Excessive suspended sediment loads can also inhibit migration, cause gill irritation, and impair feeding behavior in salmonids. One method for measuring the quantity of fine sediment is by filtering a prescribed volume of water through a specific size membrane-filter and measuring the mass of sediment captured. This is known as total suspended solids (TSS). A more common method, which can be done in the field, is to measure the amount of light scattered or absorbed by the sediment particles in a sample of water. This is known as turbidity and can be accomplished in lab or in the field using a calibrated turbidimeter. These devices measure turbidity in nephelometric turbidity units or NTUs. Currently, the Washington WQ criteria for turbidity states that turbidity shall not exceed 5 NTU over background turbidity when the background turbidity is 50 NTU or less, or have more than a 10

percent increase in turbidity when the background turbidity is more than 50 NTU. The background turbidity represents the natural ambient conditions for that stream and must be established prior to monitoring or may be determined based on reference stream conditions.

Discharge (or streamflow) is a measure of the volume of water flowing through a stream channel at a given point in time and space. Discharge or flow is typically measured in the field using a flow meter. If available, a stream stage-gage can also be used to estimate flow. Because hydrologic change is the driving force behind the main disturbance regime in streams, flow measurements made under a variety of conditions (flood, storm, baseflow, etc.) are very useful for making management decisions.

Bacterial Monitoring

The presence of some types of microbes indicates only a potential risk for water contamination. Other microbes/bacteria are pathogens themselves (i.e., known to cause disease). Pathogenic enteric bacteria enter the freshwater and nearshore environment from human and animal waste products (*Dadswell*, 1993). Direct contact with contaminated water or consumption of contaminated shellfish or finfish can lead to human health problems. Public health organizations, state environmental agencies, and the U.S.-EPA have developed several water quality criteria to protect human health. The most commonly utilized measure of fecal pathogenic bacteria is fecal coliform (FC) abundance (*Dadswell*, 1993). Coliform bacteria, in general, are only an indicator of potential public health risk, and are not actual pathogens. Typically, the geometric mean of all FC samples must be less than a specified level and no more than 10% of all FC samples must be below a higher level (14 FC/100 ml for shellfish consumption from marine AA waters and 50 FC/100 ml for class AA freshwater bodies) based on the beneficial uses of the waters in question. In addition to ecological impacts, fecal bacterial contamination of nearshore areas has a direct economic impact to coastal and estuarine communities through the loss of shellfish revenues and the restrictions placed on recreational uses.

Sources of fecal bacterial contamination include humans, domestic animals, and wild animals. The highest FC levels are typically collected in agricultural areas and in urbanized watersheds (*CWP*, 1999). Studies using genetic analysis have shown that up to 95% of the FC found in stormwater run-off is from nonhuman sources, mostly dogs and livestock (*Lim and Oliveri*, 1982; *Trial*, 1993; *Van der Wel*, 1995; *Alderiso et al*., 1996; *Samadpour and Checkowitz*, 1998). Recent studies also indicate that levels of FC contamination in nearshore areas is strongly correlated with human population, the level of watershed development, and the quantity of impervious surfaces within a drainage area (*Bannerman et al*., 1993; *Varner*, 1995; *Weiskel et al*., 1996; *CWP*, 1999; *Young and Thackston*, 1999; *Mallin et al*., 2000). Studies also show that FC is often highly correlated with water column turbidity and nutrient concentration as well as being inversely correlated with salinity (*Mallin et al*., 2000).

Fecal bacteria can enter nearshore waters directly from waterfowl or marine mammal excretion. Although the annual loading of FC into coastal and estuarine waters from waterfowl and other wildlife can be significant, the effects are generally mitigated by the often seasonal nature of these inputs, their wide distribution across the marine surface

area, and the apparent limited dispersal from their fecal pellets (*Weiskel et al*., 1996). The elution of fecal bacteria from shoreline deposits of decaying vegetation (often called "wrack") also contributes to FC loading. In addition, release of FC bacteria during the resuspension of nutrient-rich, sub-tidal sediments was found to be a minor source of FC contamination (*Weiskel et al*., 1996). High FC levels have also been found in sediments from stormwater drain-inlets and piping systems (*Marino and Gannon*, 1991). In addition, sediment from stormwater ponds (*Pitt*, 1998) and from roadside gutters (*Bannerman et al*., 1993) may also be a source of FC contamination. Direct inputs from human sources include CSO overflows, SSO overflows, illicit sewage-stormwater connections, boat discharges, sewage conveyance spills, and sewage treatment plant outfalls.

In general, on-site sewage treatment (septic) systems are often the largest potential FC source in a watershed-nearshore area (*Duda and Cromartie*, 1982; *Pitt*, 1998; *Young and Thackston*, 1999), but due to attenuation and filtering during subsurface transport very little fecal bacterial contamination usually reaches receiving waters from these widely dispersed sources. The exception to this is when septic systems have failed, are improperly designed or installed, or in areas where septic system density has overwhelmed the assimilative capacity of the native soils. The most extreme bacteria (FC) concentrations found in stormwater typically are associated with inappropriate human sewage discharges, such as failed septic systems, sanitary sewer overflows or leaks, and illicit connections to the storm drainage network. In these rare and serious situations, FC levels can be several orders of magnitude above water quality standards (*Pitt*, 1998). As a general thumb-rule, human sources of sewage should be suspected when FC levels are consistently between 10^3 and 10^6 (*Pitt*, 1998). Typically, however, FC levels in freshwater streams and drainage channels are relatively low except for stormwater run-off events or so-called "wet-weather" flows (*CWP*, 1998).

Another human-related source of fecal bacterial contamination is agricultural run-off from livestock wastes. This can be a significant source in watersheds where farming or livestock production is a major land use (*Samadapour and Checkowitz*, 1998). However, in most developed areas, the most significant source of FC input to the nearshore environment is from stormwater run-off or NPS pollution (*CWP*, 1999). This surface run-off can flow directly into estuaries or nearshore waters from developed shoreline areas via storm drain outfalls or as overland flow. In addition, fecal bacteria contamination and other NPS pollution can indirectly enter the nearshore via streams that drain developed upland watersheds. Recent studies have shown that stormwater run-off from impervious surfaces (roads, parking lots, etc.) and from stormwater drainage networks (drain-inlets, stormwater piping, and outfalls) are the most significant sources of FC contamination in urbanizing watersheds and nearshore drainages (*Weiskel et al*., 1996; *Moorhead et al*., 1998; *Young and Thackston*, 1999; *Mallin et al*., 2000). Bacterial contamination will generally settle from the water column during low-flow periods and settle into sediments. Here they can persist for weeks or even months if the sediment is moist and rich in organic material (*Burton et al*., 1987). As a result, streams and drainage ditches that drain urbanizing watersheds can be significant sources of fecal bacterial contamination to the nearshore environment. In urbanizing watersheds, bacteria contamination can come form human sources or from domestic animals or wildlife.

The transport pathway of FC contamination in developed watersheds is generally quite simple. When fecal material is deposited on or near an impervious surface, such as a road or driveway, the fecal contamination and other NPS pollutants (litter, sediment, nutrients, metals, organics, etc.) are provided with a means of concentration and rapid conveyance to downstream water bodies. During "dry" periods, fecal material accumulates on impervious areas, with little decline in FC density for up to 30 days and possibly longer, depending on ambient conditions (*Weiskel et al*., 1996). When storm events occur, these pollutants are washed off the impervious surfaces and transported downstream with stormwater run-off. The conveyance network may be in the form of roadside ditches or vegetated swales in rural watersheds. In suburban and urban watersheds the stormwater, however, the stormwater conveyance system is often much more "efficient", including curbs and gutters, drain-inlets or catch basins, and a storm-drain piping network that routes run-off directly to streams, rivers, and lakes, as well as into nearshore marine waters. Therefore, it is not just the intensity or level of development that is important to downstream pollutant loading, but the type of land-use activity, the location of that development, the amount of impervious surface area, and the type of stormwater infrastructure present (*White et al*., 2000). In a study of a shallow embayment near Buzzards Bay, MA, it was found that FC bacterial yields were 2–3 orders of magnitude greater from impervious areas served by stormwater drainage piping networks than from areas of rural or low-intensity residential land-use that were served by "unimproved" stormwater conveyance systems (*Weiskel et al*., 1996). A Wisconsin study (*Bannerman et al.*, 1993) found that residential lawns, driveways, sidewalks, and streets were the major sources of bacterial contamination. As was discussed earlier, the source of this suburban FC contamination is mostly nonhuman (i.e., domestic dogs, cats, and livestock). Except in cases where inappropriate human sewage discharge is present in an urbanized watershed, most of the bacteria present in stormwater run-off are generally from non-human sources (*CWP*, 1998).

It has also been shown that fecal bacteria counts are generally higher in urbanized watersheds that are served by sanitary sewers than in non-sewered basins (*Young and Thackston*, 1999). In these situations, FC densities are typically related to human population level, the density of development, the percentage of total impervious area (% TIA), and the domestic animal population (the so-called "Fido" hypothesis). As has been discussed, this fecal material deposited on and near impervious surfaces, such as roads and driveways, as well as residential lawns and park areas, is transported by stormwater run-off into natural streams and stormwater systems. From there, it is transported downstream to estuaries or nearshore waters. If the conveyance route includes vegetated drainage swales, vegetated filter strips, or wetland areas, the level of bacterial contamination can be significantly reduced (*Weiskel et al*., 1996; *Young and Thackston*, 1999; *Mallin et al*., 2000). In addition, if the run-off can be infiltrated and allowed to flow through the shallow groundwater layer prior to reaching downstream receiving waters (much as septic systems are designed to do), the level of FC contamination can typically be reduced even further (*Weiskel et al*., 1996; *CWP*, 1999; *Young and Thackston*, 1999; *Mallin et al*., 2000).

In summary, the sources of bacterial contamination in developed watersheds are ubiquitous and widespread. In most cases, impervious areas such as roads, driveways, sidewalks, and lawns act as source areas, collecting and concentrating pollutants during

dry weather. Rainstorms tend to wash these pollutants, including fecal material, into the stormwater drainage system and from there on into the natural drainage network and ultimately into receiving waters. In general, bacterial contamination is higher in more developed residential areas and in rural areas where livestock are present. In addition, failing on-site sewage (septic) systems are also a major source of bacterial contamination. Finally, stormwater run-off is the key mobilization and transport mechanism for bacterial contamination. Therefore, it is recommended that streams, lakes, and estuaries be monitored for FC contamination at least monthly, with storm events targeted for more frequent monitoring.

Stream Habitat Assessment

Introduction

Instream physical habitat assessment methods for small, wadable streams abound. Many agencies in the PNW region have developed their own habitat assessment protocols. The habitat assessment protocol used here differs from others in that it incorporates a variety of methods used by local agencies to come up with the most appropriate protocol for PNW DoD installations. In particular, methods utilized in this report were borrowed from the following sources:

1. Timber, Fish, and Wildlife (TFW) Ambient Monitoring Manuals (*Schuett-Hames et al*.,1999).
2. Aquatic Habitat Indicators and their Application to Water Quality Objectives within the Clean Water Act. US-EPA-910-R-99-014 (*Bauer and Ralph*, 1999).
3. Fish and Fish Habitat Standard Inventory Procedures Handbook. USDA, Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report #346 (*Overton et al*., 1997).
4. Rapid Bio-assessment Protocols. U.S.-EPA-841-B-99-002 (*Plafkin et al*., 1999).
5. Methods for Evaluating Stream, Riparian, and Biotic Conditions. USDA, Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report (*Platts et al*., 1983).
6. Monitoring Wilderness Stream Ecosystems. USDA, Forest Service, Rocky Mountain Research Station, General Technical Report (*Davis et al*., 2001).
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16. Aquatic Inventory Project: Training Materials And Methods For Stream Habitat Surveys. Oregon Department of Fish and Wildlife (*ODFW*, 1999).
17. Nature mapping for Fish and Streams. Washington Department of Fish and Wildlife (*WDFW*, 1997).
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Objectives

Before any habitat assessment is conducted, a clear purpose and justification for collecting the data must be established. Far too often data is collected and archived, but never used for any management decisions. This is often the case with data needed to meet a regulatory requirement. A monitoring strategy must be developed by first identifying the management question(s) being addressed, then determining the institutional level of effort required (and available) to make particular kinds of measurements effectively, and, finally, by identifying what specific parameters should be measured.

One of the key objectives of stream habitat assessment is to provide adequate baseline scientific information to improve decision-making by resource managers. The specific goals of the stream habitat assessment phase of this project were threefold: 1) characterize the streams in terms of their habitat for native biota (invertebrates and salmonids) with respect to reference conditions, 2) identify areas of priority for restoration and preservation, and 3) provide a *baseline assessment* for future evaluation of trends in habitat quality over time. This protocol was designed to evaluate the current conditions of the stream that have resulted from existing watershed and riparian zone disturbances, both natural and anthropogenic.

Only a limited set of parameters shows much utility or feasibility in addressing the most common management questions being faced by jurisdictions in the PNW. The parameters measured as part of the habitat assessment process were chosen to evaluate the ecological effects of typical land-use activities on ecological conditions in local streams. The parameters were selected based on the fact that they are objective in nature and generally yield consistent results. The most important criteria for selection of survey parameters was that they are representative of critical salmonid habitat features and are sensitive to the type and intensity of human disturbance. The overall goal is to correlate the variability of instream habitat characteristics and riparian conditions, as well as aquatic

biota with the level and type of watershed disturbance and to establish the linkage between these components.

Watershed and Riparian Characteristics	**=>**	**Instream Habitat Conditions**	**=>**	**Aquatic Biota**

Data obtained from these habitat assessment surveys can be used to document current stream quality and monitor changes and trends that may occur over time as a result of land-use modifications. This protocol is not meant to be a predictive, but will provide a description of baseline conditions, good or bad, from which to proceed with protection, enhancement, or restoration efforts.

Habitat Assessment

Habitat includes all those attributes that influence or support biota within the stream ecosystem. These physical conditions, chemical water quality characteristics, as well as instream biological attributes show considerable natural variation. Thus, expectations differ even in the absence of human disturbance. This is an important point, that there is not necessarily a set of critical threshold values for habitat parameters, but more likely there is an optimal range that will support a functional ecosystem. Maintaining ecological integrity requires sustaining a high level of biological, chemical, and physical integrity. Within a given eco-region, precipitation patterns, hydrology, and geomorphology are likely to be strong natural determinants of stream habitat features. It is important to understand that stream ecosystems have a natural disturbance regime and some change should be expected. In general, the quality of stream habitat is a direct indication of overall watershed quality and ecological sustainability.

Habitat attributes of aquatic ecosystems that are generally recognized as important in influencing stream ecological integrity include the following (of course, effective monitoring requires knowledge of what parameters out of this long list to measure):

- Stream channel geometry and geomorphologic characteristics
- Streambank stability or erosion
- Watershed hydrologic regime and instream flows
- Salmonid rearing habitat complexity and diversity
- Instream large woody debris (LWD)
- Salmonid spawning habitat quality and abundance
- Streambed sedimentation
- Riparian forest quality and quantity (riparian integrity)
- Physio-chemical water quality
- Biological integrity

Physical habitat conditions are a subset of what determines ecological integrity, and so measuring only physical parameters cannot provide an accurate characterization of ecological conditions. In consort with careful biological monitoring, however, these measurements can efficiently provide both evaluation of overall stream health and guidance on the most likely causative factors in urban and urbanizing systems.

In a majority of settings, the most rapid and severe stream degradation is a consequence of physical effects, particularly high flows and riparian alteration, not chemical contamination (*Horner et al*., 1997; *May et al*., 1997; *Booth et al*., 2001). Assessing the physical habitat changes and/or biological effects of human activities on streams and watersheds requires either a control (reference) site or at least an unbiased estimate of the "best case" conditions attainable. These regional reference sites should have the same land-surface form, underlying geology, soils, vegetation patterns, and climate as the streams and sub-basins under study (*Hughes et al*., 1986) and represent the optimal conditions against which urbanized streams are compared. Such reference streams in undeveloped or low-impact watersheds can also provide goals for preservation, enhancement, and restoration.

Stream Classification

Detecting and predicting the effects of land-use activity on stream habitat and aquatic biota is complicated because the responses to disturbance can occur over a variety of spatial and temporal scales (*Frissell et al*., 1986). Natural processes also interact with human-induced disturbances. Physical habitat features also vary from site to site and may, therefore, vary in sensitivity to disturbance. Nevertheless, the long-term geologic and geomorphic structure of the drainage basin can be viewed as a template, which structures the complex response of the stream system (*Frissell et al*., 1986).

The natural geomorphic characteristics of each stream should be determined before comparing the level of watershed landscape alteration and degree of degradation among streams. The reasoning is that if the morphological characteristics of each stream are known, then inferences can be drawn about the natural disturbance regime and the expected response to human related impacts.

Streams should characterized by their watersheds and landscape-level characteristics, followed by the stream segment level, the stream reach level, macro-habitat scale and finally at the micro-habitat scale (*Frissell et al*., 1986). This scheme emphasizes a hierarchal, habitat-centered view of the stream's relationship to its watershed over a range of scales in space and time. Stream responses can be assessed at various levels within this framework. Most of the physical habitat assessment work is done on the reach level, with macro-habitat characteristics noted in detail.

Often there is a need to compare channel features to a reference condition. In this situation, some form of stream channel classification or "typing" system is necessary. The geo-morphologically based approach of *Montgomery and Buffington* (1997), *Frissell et al*. (1986), or Cupp (1989) developed for the Pacific Northwest should be used because they display a clear relationship between channel "stream-type" and channel behavior that is often lacking in more purely descriptive approaches (e.g., *Rosgen*, 1994).

The *Montgomery and Buffington* (1997) methodology defines a range of stream types, of which four are particularly relevant to the PSL eco-region. Of the alluvial channels encountered in lowland watersheds and their headwater tributaries, cascades are the steepest, characterized by boulders and large cobble that form the primary roughness elements and impose a strongly three-dimensional structure to the flow. Tumbling flow around individual boulders dissipates most of the energy of the flow; streambed morphology is generally disorganized, with at most small pools that span a fraction of the total channel width. Step-pool channels, in contrast, display full-width-spanning accumulations of coarse streambed material (boulders, cobble, and LWD) that form a sequence of "stair-steps", typically one to four channel-widths apart, that separate low-gradient pools filled with finer streambed particles. The step-forming materials may be mobile but only at very high discharges. Plane-bed channels lack well-defined bed-forms and instead display long, and commonly channel-wide, sections of uniform *riffles* or *glides*. In contrast to the steeper channels any flow oscillation is generally horizontal, not vertical, but the lateral variations are insufficient to produce pronounced meanders and associated pools. The most common of the lowland stream channels, *pool-riffle channels*, have laterally oscillating flow that produces a sequence of pools at the outside of bends with corresponding bars on the inside of bends. The classification discriminates between "free" pool-riffle channels, where this distinctive morphology forms simply by virtue of the inertial characteristics of the water moving in a sinuous or meandering channel; and "forced" pool-riffle channels, where the presence of pools is closely tied to obstructions such as LWD.

Stream Segment Delineation

Prior to commencing any fieldwork, information on the stream system to be surveyed should be collected and analyzed. This table-top exercise involves both map-work and a thorough review of all available data on physical habitat, water quality, and watershed conditions (see previous sections of this report), as well as information on native biota. The use of USGS topographic maps and aerial photographs is a good first step in this process.

All survey streams should be subdivided into segments for assessing physical habitat and morphological characteristics of the channel. A combination of aerial photographs, topographic maps, and field reconnaissance surveys were used to delineate stream segments. All stream segments were classified based on a standard set of criteria (*Montgomery and Buffington*, 1997). Morphological characteristics were used as the primary criteria for segment delineation. A stream segment is defined as a section of the stream with relatively homogeneous active channel dimensions, stream gradient, channel confinement, and underlying geology. Breaking streams into segments provides a means of stratifying highly variable stream systems. Segments with similar characteristics will tend to respond to disturbance in a similar manner and can be legitimately compared to each other. Segments are then further sub-divided into smaller segments based on dominant sub-basin land use and riparian corridor characteristics. In this way, survey segments are delineated such that measurements taken reflected the influence of both natural, geomorphic features as well as local anthropogenic influences or land-use impacts. Aerial photos and field reconnaissance are also useful in delineating segments. Detailed guidance on delineating stream segments based on morphological characteristics

can be found in the *TFW Monitoring Program Method Manual for Stream Segment Identification* (*Pleus and Schuett-Hames*, 1998a).

Once the stream segments have been delineated on a basin-scale map, selection of survey reaches can proceed. Each survey reach should be representative of the physical habitat conditions in the stream segment under study. Most of the biological and physical habitat related measures require sampling a certain distance of stream to get an accurate picture of the ecological community present. Past experience indicates that a length of 40 times the channel width is necessary to cover over 90% of the features found in the stream segment. For most small, wadable streams in the PSL, a bankfull width (BFW) of about 5 m is average. Therefore, each survey reach should be at least 200 m in length. In addition, because of access limitations and logistical considerations (available manpower and time constraints), the entire segment was not always surveyed. In most cases only limited portions of a stream segment are surveyed. Survey reaches varied from several hundred meters to several kilometers long, depending on the overall segment length. It is very important that the sample reach be as representative as possible of the general habitat conditions found on the study stream segment. This means that the reach should contain a representative portion of degraded features as well as natural conditions. Detailed guidance on reach selection can be found in *Pleus and Schuett-Hames* (1998b).

Field Survey Teams

Each field survey team should consist of at least two persons, one with measurement and the other with note-taking tasks, to conduct the assessments. Assessments were conducted in an upstream direction during low flow conditions from late June to early October. Hip chain string is tied to known reference points, and personnel recorded locations of instream habitat units. Habitat units are identified as pools, riffles, or glides. Categories are kept simple to avoid compounding error due to observer differences. Several quantitative habitat parameters are measured. Pool quality index (PQI) is determined for each. Pools receive a higher rating if they are large in relation to the size of the channel and have cover for fish. Riffles are rated using a riffle quality index (RQI). Riffle quality is based on substrate composition, degree of embeddedness, and proximity of pools or wetlands.

Stream channels dominated by wetland reaches should not be evaluated using this assessment because the wetland channels were often too deep to assess, and wetland reaches cannot be appropriately evaluated using the same targets and standards applied to stream-type channel reaches. Wetlands have ecological significance to streams and their biota, but have different habitat/ physical characteristics than stream ecosystems.

Field crews will begin the survey at the downstream end of the habitat assessment reach. The survey team will locate the survey reach using a hand-held GPS receiver (follow the manufacturers instructions for operation). This will provide an accurate reference location for future monitoring efforts and an input to the GIS. If a GPS receiver is not available, note the location of the survey based on geographic position such as a bridge or road crossing. Sometimes field conditions will require some adjustment in location of the sample reach from the planned or mapped location. This is acceptable. The important point is that the reach be fairly representative of conditions within the stream segment.

The sample reach should be marked or flagged at 100-meter intervals to allow for future monitoring and data comparison. Photographs should be taken of unusual and/or interesting features and at each 100-m survey reference point. The initial reference point should be assigned the zero (0) value and each successive survey point should be marked in increments of meters moving upstream. Place flags or markers well back from the edge of the channel and on fairly large objects (trees, poles, etc.) so that they will not be easily washed away. Proceed up the center of the active channel (the thalweg), following the curvature of the stream while measuring the distance from the last reference point using a hip chain or measuring tape (Figure 6). Detailed guidance on reference point selection can be found in *Pleus and Schuett-Hames* (1998b).

Field Survey Equipment

Laminated topographic maps (USGS 7.5 minute quad -1:24000 scale) and aerial photos of the stream reaches with overlays depicting roads, streams, parcels, and wetlands were used as base maps for field work. Permanent marking pens were used to indicate locations of various features and to identify survey reaches. Survey teams of two to three trained individuals were equipped with a hip chain for measuring distance surveyed, a graduated wading staff (marked in meters and tenths) for making habitat unit and LWD measurements, field maps, field data sheets, a field notebook, and a digital camera. Field gear also included a fiberglass measuring tape, day pack, polarized sunglasses, clinometer (for gradient measurements), clipboard, vest, and flagging. Field crews wore neoprene chest waders, wading shoes, and/or hip boots (non-slip soles of felt, studded "corkers", outdoor carpet or similar material are advised), rainwear, and thorn proof clothing appropriate for the weather.

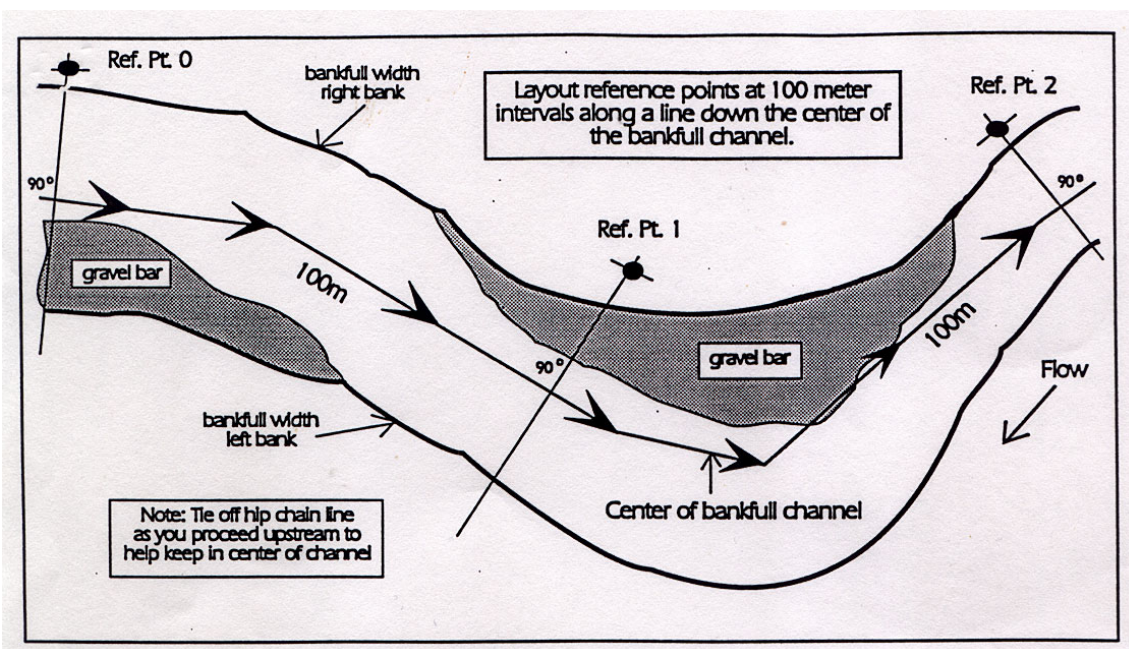

Figure 6. *Stream reach and reference point layout (*Schuett-Hames et al.*, 1999b)*

Physical Habitat Characterization

The physical habitat assessment protocol consists of several component parts. Measurements of each component are recorded on field habitat assessment data sheets. The procedures for conducting each component section of the survey are discussed in detail in the following sections and outlined briefly below:

- The survey includes a longitudinal survey of channel morphological characteristics. This included bankfull width (BFW), bankfull depth (BFD), flood-prone width (FPW), channel confinement, gradient (an indicator of flow energy potential), and other characteristics of channel geometry. Streambank erosion or stability should also be estimated using a standard scale developed for the PSL eco-region. This data was recorded at least every 50 m of survey length.
- Measurements and/or visual assessments of riparian buffer width, riparian vegetation structure, riparian canopy cover, and human disturbance in the riparian corridor (out to 50 m on both sides of the stream, minimum) are an integral part of the survey protocol. This data is also recorded at least every 50 meters of survey length.
- A major component of the habitat assessment process is the evaluation of instream salmonid spawning and rearing habitat. This includes the classification of habitat types (pools, riffles, and glides), as well as quantitative measurements of pool surface area and residual pool depth (RPD). Pool quality is also evaluated using a pool quality index (PQI) scoring criteria. Riffle surface area is also measured, along with riffle quality in the form of a riffle quality index (RQI) scoring criteria.
- The survey also includes a continuous tally of LWD along the reach as a whole, to include number of pieces, volume, location in the channel, and LWD quality (decay class and whether the LWD was coniferous or deciduous). LWD data provide an excellent measure of stream habitat complexity.

Channel Morphological Characteristics

The channel dimensions (width and depth) and geometry or shape of a stream channel tends to reflect the discharge and sediment load of the stream network, as well as conditions in the upstream drainage basin (*Montgomery and Buffington*, 1997). In general, channel dimensions are established during so-called dominant discharge events (*Carling*, 1988). Channel dimensions typically reflect these hydraulic conditions during "bankfull" or channel-forming flows, and as such are good parameters to measure. Bankfull width (BFW) and bankfull depth (BFD) refer to the average width and depth of the channel under bankfull flow conditions. To measure BFW and BFD, the edges of the active bankfull channel must be established (Figures 7 and 8). *Dunne and Leopold* (1978) devised a combination of indicators of bankfull channel boundaries. These include streambank slope, vegetation changes, and substrata composition. To measure BFW, stretch the tape from one boundary to the other, perpendicular to the channel flow

direction. If a side-channel is present, add the BFW of the side-channel to the main channel measurement. With the tape securely stretched across the channel, measure BFD at regular intervals of 0.5 m. The number of intervals will depend on channel width. BFD is the average distance from the streambed to the estimated active channel water level at bankfull flow. Bankfull channel measurements (BFW and BFD) should be made at regular intervals as the survey team moves up the sample reach. The 50-m intervals used for this project are recommended for typical surveys to obtain adequate data for a statistically valid measure. Flood-prone width (FPW) is estimated by measuring the channel width at twice the BFD or by direct measurement of the floodplain width or channel migration zone (CMZ).

Channel confinement is classified as unconfined (U), moderately confined (M), or confined (C) based on valley slope and development encroachment. If the stream has been channelized or artificially confined this should be noted in the comments section. Stream gradient or slope is useful in two different ways. First, the overall stream gradient is one of the major stream classification variables, giving an indication of potential water velocities and stream power; both of which are in turn important controls on aquatic habitat and sediment transport within the reach. Second, the spatial variability of stream gradient is a measure of habitat complexity, as reflected in the diversity of water velocities and sediment sizes within the stream reach. Gradient is usually measured from the topographic map, prior to going into the field and is then re-measured locally using a hand-held clinometer. As is the case with most standard stream assessment protocols, this assessment delineated streams into segments based primarily on gradient, valley-channel confinement, and habitat type (i.e., streams, wetlands, and lakes). This delineation technique is designed, in part, to recognize the inherent capacity of the stream to support a variety of salmonid species. For this project a gradient-confinement matrix was developed to identify potential spawning and rearing habitat for each salmonid species (Tables 7 and 8). In the absence of definitive information on salmonid utilization (current or historic), the criteria in these tables were used to determine potential salmonid species utilization. Sinuosity of the channel (ratio of the length of the stream reach to the valley length) is also a useful stream classification characteristic and may be an indicator of human influence. Sinuosity can be measured using the topographic map prior to going into the field.

In summary, BFW and BFD measurements can generally be made quickly and require limited equipment. These measures are the primary variables for relating channel size to watershed parameters such as area, flood frequency, or level of development. However, experience is necessary to identify bankfull height consistently because a variety of indicators are needed to identify it reliably (*Scholz and Booth*, 2001), and some uncertainty in reported bankfull channel dimensions is almost inescapable (*Johnson and Heil*, 1996). Documented channel changes can be very useful in trend analysis. For example, cross-section data can be used to identify changes in channel geomorphology over time (*Leopold*, 1973; *Dunne and Leopold*, 1978; *Booth*, 1997; *Booth and Henshaw*, 2001) with almost no risk of subjective misinterpretation. Bankfull channel dimensions can be measured more rapidly than full cross sectional areas, but documenting change in bankfull channel dimensions requires a greater magnitude of channel change than for cross sections. With an adequate regional compilation of channel dimensions, these measurements can show the relative deviation of channel geometry from anticipated

undisturbed conditions (*Dunne and Leopold*, 1978; *Booth and Jackson*, 1997; *Booth and Henshaw*, 2001). They can therefore help evaluate current conditions and prioritize streams for rehabilitation.

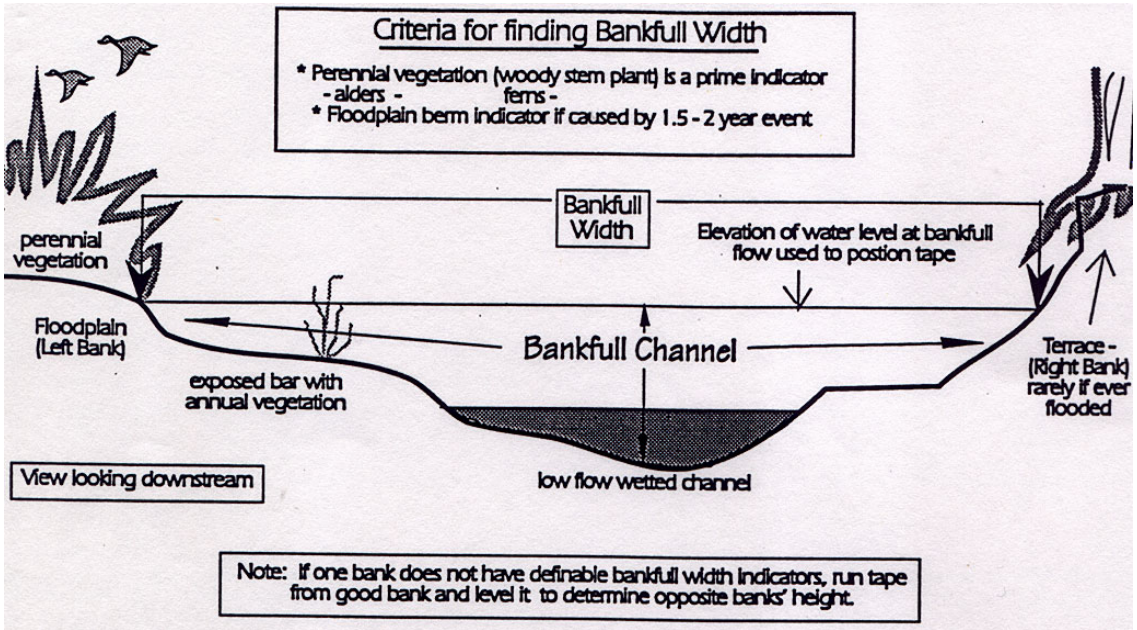

Figure 7. *Bankfull width (BFW) determination (*Schuett-Hames et al.*, 1999b)*

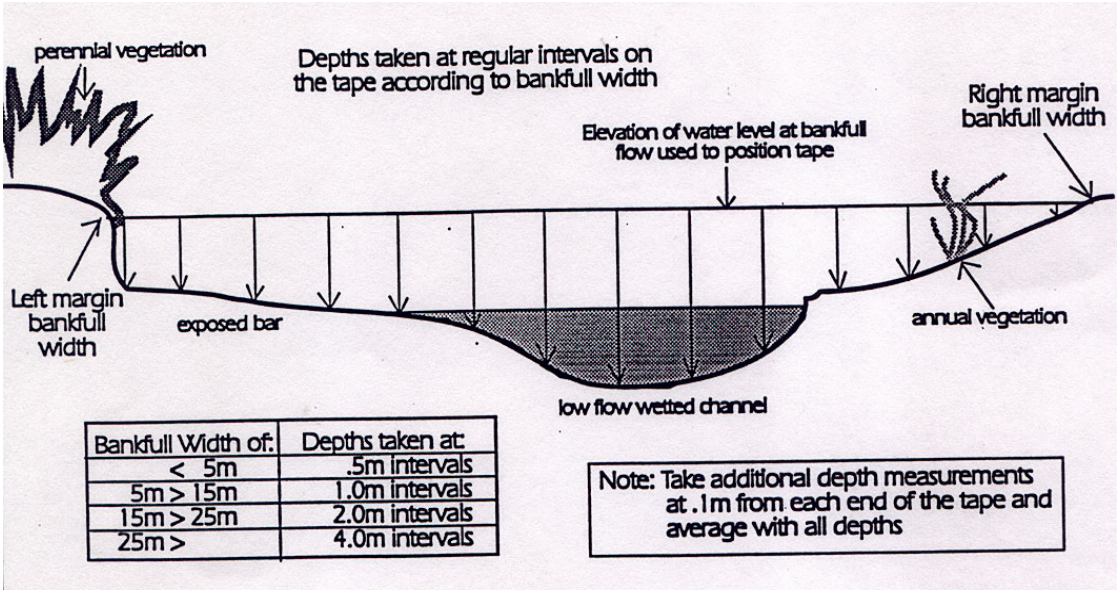

Figure 8. *Bankfull depth (BFD) determination (*Schuett-Hames et al.*, 1999b)*

Table 7. *Potential salmonid rearing habitat*

Channel Confinement	**Gradient**					
	<2%	2-4%	4-8%	8-12%	12-20%	>20%
Unconfined (VW>4CW)	Coho Chum chinook Steelhead Cutthroat	Coho Chinook Steelhead Cutthroat	Steelhead Cutthroat	Steelhead Cutthroat	Cutthroat	N/A
Moderately Confined (2CW<VW<4CW)	Coho Chum chinook Steelhead Cutthroat	Coho Chinook Steelhead Cutthroat	Steelhead Cutthroat	Steelhead Cutthroat	Cutthroat	N/A
Confined (VW<2CW)	Coho chinook Steelhead Cutthroat	Coho Chinook Steelhead Cutthroat	Steelhead Cutthroat	Steelhead Cutthroat	Cutthroat	N/A

Note: VW = Valley Width and CW = Channel (bankfull) Width

Table 8. *Potential salmonid spawning habitat*

Channel Confinement	**Gradient**					
	<2%	2-4%	4-8%	8-12%	12-20%	>20%
Unconfined (VW>4CW)	Chum Cutthroat	Coho Chinook Steelhead Cutthroat	Coho Steelhead Cutthroat	Steelhead Cutthroat	Cutthroat	N/A
Moderately Confined (2CW<VW<4CW)	Chum Cutthroat	Coho Chinook Steelhead Cutthroat	Coho Steelhead Cutthroat	Steelhead Cutthroat	Cutthroat	N/A
Confined (VW<2CW)	Chum Cutthroat	Coho Chinook Steelhead Cutthroat	Steelhead Cutthroat	Steelhead Cutthroat	Cutthroat	N/A

Note: VW = Valley Width and CW = Channel (bankfull) Width

Streambank Erosion and Stability Rating

Streambank erosion and bank stability describe the physical condition of the stream bank by characterizing the amount of bank erosion present and the relative stability of the bank. Measuring bank erosion, particularly in watersheds with a great deal of human activities, is a critical parameter for assessing channel conditions relative to natural stream systems and for guiding rehabilitation, because it is one of the few ways available to recognize the hydrologic disturbance that typically accompanies watershed development (*Hollis*, 1975; *Booth*, 1991; *May et al.*, 1997).

The method recommended here is based on a verbal ranking system, with or without a photographic record, as this information requires minimal effort, generally describes current conditions, is useful for some level of trend analysis, and can locate areas for habitat restoration. Established channel assessment methods typically divide the observed range of bank (in)stability into several distinct categories of descriptive conditions, which appears to be a useful and replicable degree of detail. *Henshaw* (1999) has developed a descriptive characterization based in part on an earlier technique used in the PSL region (*Booth*, 1991). This method has particularly good applicability to this region and has been shown to be replicable. In contrast, more laborious measurements of bank erosion are rarely of much use. For example, identifying the length and location of an erosional zone and plotting it on a map can increase the precision of the original measurements but requires substantially more training and more field time. The utility of such measurements is uncertain—unless the purpose is to identify specific sites for bank repair, such data are commonly used simply to indicate those reaches, in aggregate, that display a relatively high degree of erosion. If the specific sites themselves will never be resurveyed, the detailed description of their location or character will not be used for either current assessment or subsequent remediation.

In each 50-m section of the survey reach, the streambank erosion and stability conditions should be noted. Bank erosion and scour are important indicators of excessive flows due to human activity in the watershed as a whole, and the stream channel in particular. The average condition of both streambanks should be estimated. Categories to be used are shown in Table 7. Streambank vegetative cover should also be estimated for each 50 m sample reach. This should be noted as a percentage of bank cover for each side of the stream. Artificial streambank protection or "rip-rap" is considered a sign of bank instability and is assigned a score of "1", whereas undercut banks or mass-wasting sites may be either natural or human influenced. Note any artificial bank protection in the comments section.

Table 9. *Streambank stability and erosion classification criteria (*Henshaw, 1999*)*

Class	Description
4	STABLE • perennial vegetation to waterline • no raw or undercut banks (some erosion on outside of meander bends OK) • no recently exposed roots • no recent tree falls
3	SLIGHTLY UNSTABLE • perennial vegetation to waterline in most places • some scalloping of banks • minor erosion and/or bank undercutting • recently exposed tree roots rare but present
2	MODERATELY UNSTABLE • perennial vegetation to waterline sparse (mainly scoured or stripped by lateral erosion) • bank held by hard points (trees, boulders) and eroded back elsewhere • extensive erosion and bank undercutting • recently exposed tree roots and fine root hairs common
1	COMPLETELY UNSTABLE • no perennial vegetation at waterline • banks held only by hard points • severe erosion of both banks • recently exposed tree roots common • tree falls and/or severely undercut trees common

Riparian Zone Assessment

Numerous studies have demonstrated a close correlation between riparian corridor integrity and the maintenance of natural instream habitat conditions (*Steedman*, 1988; *May et al*., 1997; *May and Horner*, 2000), and so this stream ecosystem feature has particular value in stream habitat assessment. There are several parameters that are typically measured to assess riparian conditions in PNW streams. These include canopy cover, riparian vegetation type, forest maturity, and riparian extent. Riparian canopy cover over a stream is important not only in its role in moderating stream temperatures through shading, but also as an indicator of conditions that control bank stability (tree root systems), and the potential for input of coarse and fine particulate organic material. Organic inputs such as leaf-litter and woody material from riparian vegetation become food for stream organisms and add structure (LWD) to create and maintain complex channel habitat. The two most common parameters measured are canopy closure and canopy density. *Canopy closure* is the amount of vegetation overhanging a stream (i.e., sky area containing vegetation) and does not depend on the presence of leaves. *Canopy density*, often referred to as angular canopy density, is the sky area blocked by vegetation, which can vary seasonally if the dominant riparian vegetation is deciduous. The measurement of canopy closure provides an indirect measure of the degree of shading afforded the stream by the adjacent riparian vegetation.

Vegetative canopy cover over the stream should be measured at 50-m intervals. This is normally done using an instrument called a (convex spherical) densiometer (*Lemmon*, 1957). Characterization of riparian vegetation using this parameter can be readily used to accurately describe both current conditions and long-term trends within the stream corridor. However, use of a densiometer does require some training and may be unnecessarily time consuming for some applications. In most cases, a visual estimation technique can be utilized. Canopy estimates made using several percentage classes are adequate for most applications. These measurements can be performed readily in the field with good replicability and limited training. However, unaided estimates of percent canopy are prone to some observer error and are less precise than measurements made with a densiometer, and so they will not be nearly as sensitive to changes over time.

Visual estimates should be taken separately in four directions standing at the center of the stream; facing upstream, facing downstream, facing the left bank, and then facing the right bank. These measurements were used to estimate canopy cover over the channel at each 50-m survey point. The following visual estimate classes were used for this project:

- 80–100% canopy cover = 4
- 60–80% canopy cover = 3
- 40–60% canopy cover = 2
- 0–40% canopy cover = 1

Riparian zone integrity, based on the quantity and quality of riparian forest areas, is also assessed at this time, although much of this assessment can be done in the office using aerial photographs. Field surveys can be utilized to update the aerial photographs where photographic coverage is not up to date or adequate. The longitudinal integrity of the riparian corridor is determined based on the number of significant breaks in the riparian zone/km, including breaks due to roads, trails, utility right-of-ways, and storm sewer outfalls, regardless of the type or width of the discontinuity.

Riparian forest characteristics are also noted for 50-m sections of the survey reach. The type of vegetation (deciduous, coniferous, or mixed) and the stand-age or successional stage are recorded. The average width of the riparian buffer zone is also estimated for both sides of the stream channel. This data is then used to supplement and verify any riparian zone aerial photo interpretation. Riparian vegetation composition is also visually estimated for each channel reach. The presence of invasive plant species should also be noted. Dominant and subdominant riparian vegetation categories are described for the right and left banks using the following categories:

- Forest (coniferous, deciduous, or mixed)
- Shrubs and/or brush/scrub vegetation
- Tall herbaceous (e.g., natural field or meadow)
- Short herbaceous (e.g., golf course, pasture, etc.)
- Impervious (e.g., buildings, roads, asphalt, etc.)
- Residential landscaped (mowed lawn with ornamental shrubs/trees)

One of the many important functions of the riparian corridor, with respect to maintaining stream ecosystem integrity, is to provide instream LWD. The ability of a buffer to supply LWD over time is partly dependent upon buffer width. It has been estimated that a 10-m riparian buffer will supply about 20% of LWD of a mature, forested stream-riparian ecosystem, a 30-m buffer approximately 70% of LWD, and a 50-m buffer 90% of LWD (*FEMAT*, 1996). For this assessment buffers greater than 50 m (150 ft) in width are considered low impact, 30–50 m (100–150 ft) moderate impact, 10–30 m moderately-high impact, and < 10 m in width high impact.

- The LWD recruitment potential of the riparian zone is evaluated for each survey reach based on the following criteria:
- Mature coniferous riparian with adequate LWD = 4 (High)
- Mixed mature riparian or without adequate LWD = 3 (Moderate)
- Mature deciduous riparian or young coniferous forest and/or without adequate LWD = 2 (Low)
- Lack of riparian forest <u>and</u> little or no LWD = 1 (Non-Supporting)

Mature trees were those with a diameter at breast height (DBH) of > 20 inches and a young forest is classified as having an average DBH < 12 inches. A forest with an average DBH of 12–20 inches is considered as maturing (*WDNR*, 1997). A forest is considered coniferous-dominated if it is > 70% coniferous species in composition and is deciduous-dominated if it is > 70% deciduous species.

Instream Habitat Classification and Assessment

Instream habitat features are the result of the interaction between the stream hydrologic regime and the geomorphic structure of the channel. Habitat composition provides the basis for a relatively direct link between the physical processes governing stream morphology and the suitability of the stream for fish reproduction and growth. The spatial distribution and abundance of different habitat units is critical to the relative success of various aquatic biota. Natural factors such as stream size, gradient, and channel confinement influence the type and relative abundance of habitat units present. In addition, the relative abundance and characteristics of habitat features also responds to changes in local and watershed scale processes that effect sediment supply, stormwater run-off, and LWD recruitment. These watershed processes are strongly influenced by human activities. Instream habitat quantity and quality is critical to the survival of native salmonid populations. Each species of salmon and trout have specific habitat requirements based on different life histories. However, there are a number of physical habitat factors common to all salmonids. All salmonids need adequate spawning (riffles) and rearing (pools) habitat, although the specific characteristics may differ for each species and geographic location. All salmonids also need cover and complexity in their physical environment. These are the habitat features that this protocol targeted.

Characterizing instream physical habitat has a long history in the forested watersheds of the PNW. This approach is intuitively well founded—if a primary interest is the ability of the channel to support aquatic organisms, what better way to assess that ability than to

measure the features of the channel directly associated with biological use? Two factors limit the utility of direct measures of channel habitat features (*Scholz and Booth*, 2001):

1. The measurement or characterization of such features is imprecise and subject to substantial observer error. This is true of most monitoring parameters, however, the magnitude of typical errors associated with habitat surveys may actually render data inappropriate for between-stream or time-trend comparisons.
2. In-channel physical habitat features do not necessarily respond rapidly to human disturbance, and so even if a measurable change in such a monitoring parameter can be documented it may come far too late to trigger an effective management response.

Both of these limitations have been the subject of an extensive, recent literature review and analysis (*Poole et al*.,1997). The basis for these conclusions is, in part, the work of four studies that have specifically investigated observer bias (*Platts et al*., 1983; *Hankin and Reeves*, 1988; *Ralph et al*., 1991; *Roper and Scarnecchia*, 1995). Their conclusion is as follows:

> Habitat-unit classification was not designed to quantify or monitor aquatic habitat. At the level necessary for use as a stream habitat monitoring tool, the method is not precise, suffers from poor repeatability, cannot be precisely described or accurately transferred among investigators, can be insensitive to important human land-use activities, is affected by stream characteristics that vary naturally and frequently, and is not based on direct, quantitative measurements of the physical characteristics of interest. Relying on habitat-unit classification as a basis for time-trend monitoring is time-consuming, expensive, and is not advised (*Poole et al*., 1997).

Even if high precision could be achieved, a variety of researchers have noted the relative insensitivity of habitat units to land-use changes or other human impacts (*Warren et al*., 1987; *MacDonald et al*., 1991; *Ralph et al*., 1994). Despite the generally poor record for habitat assessment in monitoring programs, the underlying value of including some aspect of these physical habitat features among the list of monitoring parameters must be acknowledged. Useful results are most likely where the number of habitat categories is small. *Roper and Scarnecchia* (1995) reported complete agreement among their multiple observers for only 25% of the classified units, using their full set of nine categories. In contrast, their observers achieved a more useful 75 percent agreement when only three units were being discriminated (pools, riffles, and glides). This protocol recommends using only pools, riffles, and glides because they show a crude but consistently inverse correlation with human watershed disturbance across a wide range of landscape types (*Booth*, 1990; *Peterson et al*., 1992; *May et al*., 1997). Even with this consideration in mind, substantial observer variability, seasonal variability in flow, and variability caused by instream objects such as LWD make measuring and interpreting habitat data problematic.

Habitat units are identified as pools, riffles, or glides (Figure 9). Categories were kept simple to avoid compounding error due to observer differences (*Hubert and Bergersen*,

1998). The length, maximum *thalweg* depth (deepest part of the channel), BFW, BFD, as well as the residual pool depth (RPD) are also measured. Pool Quality Index (PQI) is determined for each pool. Pools receive a higher rating if they are large in relation to the size of the channel and have cover for fish. Riffles are rated using a riffle quality index (RQI). Riffle quality is based on substrate composition, degree of embeddedness, and proximity of pools or wetlands.

Habitat units are defined as:

- Pool: Slow water, with cover (LWD, over-hanging vegetation, etc.). Subcategories define the general type of pool, and include scour (lateral, channel, channel confluence, plunge), dam, and backwater.
- Riffle: Swiftly flowing, turbulent water; some partially exposed substrate; substrate gravel, cobble and/or boulder dominated;
- Glide: Wide, uniform channel volume, low to moderate water velocity, little surface agitation and little or no cover.

In summary, the habitat assessment section of the protocol includes in-channel assessments of habitat units and an inventory of large woody debris. The stream-habitat surveys were patterned after standard procedures used to assess physical habitat in forested streams (*Bisson et al*., 1987; *Lisle*, 1987; *Hankin and Reeves*, 1988; *Robison and Beschta*, 1990; *Peterson et al*., 1992; *Ralph et al*., 1994). Three main features were recorded: pools (rearing habitat), riffles (spawning habitat), and LWD. Habitat is assessed during the low-flow period between June and September. A detailed description of the stream assessment protocol used is located in *Pleus et al*., 1999; *Schuett-Hames et al*., 1999a; and *Schuett-Hames et al*., 1999b.

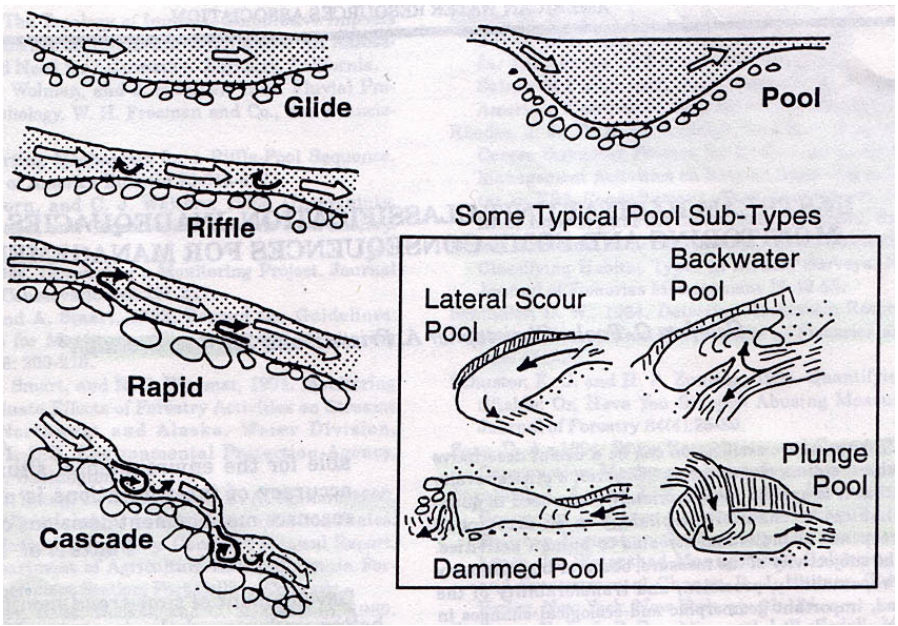

Figure 9. *Basic habitat units (*Poole et al*., 1997)*

Tributaries, Wetlands, Side Channels, and Outfall Pipes

Tributaries, wetlands, and side channels entering or adjacent to the stream, and location, size, and function of pipes should also be noted. In addition, any obvious problems or concerns such as point of discharge or withdrawal for each reach should also be described.

Instream Biota

Presence of juvenile and/or adult fish, freshwater mussels, amphibians and other biota should be noted on the field data sheets. Juvenile salmonids, however, were usually identified to species where possible and an approximation or impression of numbers or abundance was recorded. These observations were reported; however, the reader should take into account that these are field notes and represent a brief snapshot in time and not a formal assessment of fish abundance. In addition, it should be noted that lack of an observation does not imply absence of a species from these sites.

Photographs

Digital photographs depicting the general nature of each characterized reach or notable features should be taken as the field team proceeds upstream.

Salmonid Rearing and Spawning Habitat Assessment

Most stream fishes utilize specific instream habitat types during different life-stages (*Bisson et al*., 1982). Salmonids are no exception to this rule. Within salmonid populations, competition and territoriality plays an important role in stream habitat selection and utilization. This is particularly true of the juvenile life-stage. When food is limited, such "density-dependent" interactions result in habitat partitioning of sympatric populations and intra-species age-classes (*Glova*, 1984). In general, juvenile coho salmon prefer deep, slow-water pools formed by LWD (logs and root-wads), whereas juvenile steelhead prefer riffles and lateral scour pools with faster water and cover provided by LWD, overhanging vegetation, or undercut banks (*Bisson et al*., 1982). Cutthroat are generally competitively displaced and are opportunistic in their choice of habitat types, able to survive in pools, riffles, or glides provided cover (LWD) is present (*Hartman*, 1965; *Bisson et al*., 1982; *Glova*, 1984; *Bugert et al*., 1991; *Heggenes et al*., 1991). Juvenile salmonids move within their stream system to take advantage of seasonal environmental changes (*Bustard and Narver*, 1975). Juvenile coho often seek refuge from high stormflows and over-winter in off-channel (floodplain) ponds or wetlands (*Levy and Northcote*, 1982; *Tschaplinski and Hartman*, 1983; *Brown and Hartmann*, 1988).

Adequate pool area and residual depth, along with sufficient cover are the keys to successful salmonid rearing. Studies have consistently indicated that the optimum pool-riffle ratio for coho production and over-winter survival is approximately 1:1 (*McMahon*, 1983; *McMahon and Hartman*, 1989; *Nickelson et al*., 1992). Coho often shift habitat preferences as the seasons change, due primarily to changes in flow and usable stream area. In winter, coho prefer off-channel, backwater or wetland pools and in summer they show a preference for main-channel pools formed by LWD (*McMahon and Hartman*, 1989; *Nawa et al*., 1990; *Nickelson et al*., 1992). Most studies have concluded that winter habitat is the most limiting factor in streams impacted by human activities within

the watershed (*Nickelson et al*., 1992). This is mainly due to the lack of instream habitat complexity normally provided by the abundant LWD found in natural streams. With adequate LWD and complex habitat features less fish are lost due to flooding washout and there tends to be greater overall fish diversity (*Pearsons et al*., 1992). Timber harvest, road-building, and urban development are all activities that tend to reduce LWD and instream pool habitat.

Large woody debris (LWD) is an integral and ubiquitous component of streams in forested watersheds of the PNW. Instream woody debris influences the physical, chemical, and biological processes occurring within the stream. LWD traps allochthonous organic matter, which represents a substantial portion of the energy base of the stream (*Bilby and Likens*, 1980; *Bilby*, 1981; *Bilby*, 1984). LWD also influences the transport and storage of sediment within the channel (*Nakamura and Swanson*, 1993). The morphological significance of large organic matter has been discussed. In the PNW, variations in channel sinuosity, gradient, and width are often regulated by LWD (*Nakamura and Swanson*, 1993). LWD can have a significant local influence on channel form, including formation of mid-channel bars, meander cutoffs, and the pool-riffle sequence (*Keller and Swanson*, 1979). Riparian forests play a key role in the control of stream channel morphologic features. These "biophysical" interactions are particularly important to the stream ecosystems of the PNW (*Rot*, 1995). Riparian forests also stabilize the active floodplain and are the primary source of LWD. In turn, LWD plays a key role in the formation of riparian forests. LWD deposited in the active channel provides sites for vegetative colonization on forested islands and in floodplain areas (*Fetherston et al*., 1995).

In the streams of the PSL, organic debris enters the stream channel as a result of bank erosion, hillslope mass-wasting events, and blow-downs. The zone from which LWD is supplied to the channel varies as a function of riparian forest composition, valley landform, and stream characteristics (*Steinblums et al*., 1984; *Grette*, 1985; *Murphy and Koski*, 1989; *Fetherston et al*., 1995). Much of the woody debris entering small, unconstrained channels, such as those common to the PSL, is introduced as a result of undercutting of trees located on streambanks (*Grette*, 1985). It has been found that 70-90% of riparian zone input of LWD originates from within 30 m of the stream channel, but as the forest becomes more mature and conifer-dominated, the proportion of input from beyond 30 m increases (*Van Sickle and Gregory*, 1990).

In general, smaller stream channels (low-order) contain the largest quantity (numbers of pieces) of LWD and have the highest LWD frequency (pieces/length of stream). In larger (higher order) channels, woody debris is more easily transported (*Bisson et al*., 1987). Larger stream channels tend to have larger sized LWD and also a greater frequency of debris jams and accumulations of LWD (*Bilby and Ward*, 1991). The quantity and distribution of LWD is also influenced by the riparian forest composition and age. Streams flowing through mature stands of cedar, hemlock, and fir in the PNW, tend to contain a larger quantity of woody debris with larger average-size pieces than streams within young and/or deciduous riparian zones (*Bilby and Ward*, 1991). LWD derived from conifers, especially Western Red Cedar, not only tends to be larger than deciduous species (predominantly Alder and Maple), thus reducing the chance of being

washed downstream, but also have significantly greater resistance to decay, resulting in increased longevity as instream structural components (*Harmon et al*., 1986).

Human activities within the riparian zone have been shown to have adverse impacts on LWD abundance, distribution, and function (*Sedell et al*., 1984; *Grette*, 1985; *Murphy et al*., 1986; *Murphy and Koski*, 1989; *Bilby and Ward*, 1991). Even if instream debris is left undisturbed during clearing of riparian forests, the quantity and quality of LWD declines over time because second-growth forests or urbanized riparian zones are unable to provide sufficient debris to replace that which is washed downstream or naturally decays (*Grette*, 1985; *Andrus et al*., 1988; *Murphy and Koski*, 1989). Under natural conditions, the quantity, size distribution, and species composition of organic debris varies considerably depending on stream size and riparian forest structure (*Bilby and Ward*, 1989). Depletion rates are inversely proportional to LWD diameter, showing the importance of mature riparian trees to the maintenance of instream structure (*Murphy and Koski*, 1989). Recovery of LWD recruitment potential to natural levels (i.e., pre-logging or urban clearing) can take more than 100 years (*Grette*, 1985; *Bisson et al*., 1987; *Bilby and Ward*, 1989). In general, small, undeveloped streams tend to have an abundance of LWD, while impacted channels tend to contain less LWD, smaller pieces, and have more LWD concentrated in debris jams.

There is no other structural component as important to salmonid habitat, in PNW streams, as LWD. LWD provides structure to the stream ecosystem and critical habitat for salmonids (*Andrus et al*., 1988). LWD performs many critical functions in forested, lowland streams. This includes maintaining the hydraulic stability of key habitat features, especially pools (*Bilby and Ward*, 1991). LWD also dissipates flow energy during peak flow events providing high-flow refuge, protecting streambanks from erosion and thus reducing sediment generation (*Bilby*, 1984), helps stabilize streambeds to minimize scour, and provides cover and habitat diversity (*Harmon et al*., 1986). Human activities, such as timber harvesting within the riparian forests of PNW streams have a adverse impact on LWD, instream habitat quality, and juvenile salmonid diversity (*Bryant*, 1983; *Murphy et al*., 1986; *Hicks et al*., 1991; *Reeves et al*., 1993). Urbanization has similar impacts, but may be even more long-lasting, especially from a hydrological standpoint. In addition to the loss of hydraulic roughness (flow energy buffer) and channel stabilizing capacity, the reduction of in-channel LWD has a major effect on instream habitat complexity and diversity. LWD is the single most important pool-forming structure in streams of the Pacific Coast and PSL eco-regions (*Grette*, 1985; *Crispin et al*., 1993). LWD also provides the most desirable cover for coho salmon and other salmonids, especially during winter, high-flow periods (*McMahon and Hartman*, 1989). With the loss of in-channel structure, there is a morphological shift away from the characteristic pool-riffle habitat to a glide-dominant channel form. There is a decrease in rearing (pool) habitat both from a quantitative and qualitative perspective. Coho in small streams have a very strong preference for structurally complex cover and low-flow microhabitats associated with organic debris (*McMahon and Hartman*, 1989). Communities of aquatic biota in general, and salmonids in particular, depend on instream habitat complexity provided by LWD (*Harmon et al*., 1986). There is no question that the complexity of LWD accumulations in small lowland streams are important to salmonid populations.

The sand, gravel, and cobble that makes up the substrata of PNW streams, also plays a vital role in determining how the ecosystem of the stream will function. Substrata size distribution and spatial arrangement influences (physical) channel hydraulics. The substrata provides benthic habitat for macroinvertebrates and bottom-dwelling fish (sculpins). Periphyton and macrophytes also depend on the substrata composition. With respect to salmonids, the streambed substrata is critical to the level of spawning success, incubation, and survival to emergence (STE). Each species of salmonids has specific preferences for gravel size and composition for spawning (*Kondolf and Wolman*, 1993), but all salmonids require spawning gravels that are highly permeable and relatively free of fine sediment (*McNeil*, 1966; *Chapman*, 1988; *Crisp and Carling*, 1989). In the process of building their redds, salmonids actually 'winnow" the fine sediment from the streambed gravels thus improving the interstitial flow of water to the incubating eggs within the redd (*Kondolf et al*., 1993). Survival to alevin emergence has been shown to be strongly correlated to the percentage of fine sediment ("fines") in the substratum (*Chapman*, 1988). Excess fine sediment also has an adverse impact on habitat suitability and survival for benthic macroinvertebrates (*Cordone and Kelley*, 1961; *Cline et al*., 1982; *Lemly*, 1982). The percentage of fine sediment (% fines) < 0.85 mm in diameter as determined by standard substrate sampling methods (McNeil Sampler) and sorted using standard sieves, is the most widely accepted measure of spawning gravel quality. Elevated levels of fine sediment in spawning gravels have been associated with timber-harvest activities, mining, grazing, and other human activities (*Beschta*, 1978; *Cederholm and Salo*, 1979; *Shirazi and Seim*, 1981; *Everest et al*., 1987; *Campbell and Doeg*, 1989; *Scrivner and Brownlee*, 1989; *Eaglin and Hubert*, 1993).

Anthropogenic activities in the watershed can also have detrimental effects on salmonid spawning habitat (*Bisson et al*., 1992). Some studies indicate that the optimum, natural pool to riffle ratio for salmonid production and over-winter survival is one that is relatively balanced (*Nickelson et al*., 1992). In addition, streambed substrate is also critical to spawning success, incubation, and survival to emergence for salmonids. Each salmonid species has a specific preference for spawning habitat conditions (*Kondolf and Wolman*, 1993), but all salmonids require spawning gravels that are highly permeable and relatively free of fine sediment (*McNeil*, 1966; *Chapman*, 1988; *Crisp and Carling*, 1989). The substrate also provides benthic habitat for macroinvertebrates, freshwater mussels, and bottom-dwelling fish such as sculpin. Increased over-land flow (including run-off) and stream bank erosion caused by anthropogenic activities in the watershed contribute to sediment deposition in the interstitial spaces of spawning gravels. This sediment suffocates biota reliant on well-oxygenated intergravel flow (*Hartman and Brown*, 1987). The % fines in PSL streams is also strongly correlated with the level of urbanization in the upstream basin (*May et al*., 1997).

Salmonid Rearing Habitat

In general, the quantity and quality of pool habitat is considered the best measure of salmonid rearing habitat in small streams. Pool habitat units within each survey reach are identified and tallied. To be considered a pool the habitat unit must possess two characteristics. A pool should have almost no visible water velocity (still or very slow moving water) and should provide some cover for juvenile or adult salmonids (Figure 10). Cover can consist of LWD, boulders, over-hanging vegetation, or under-cut banks.

In some cases, adequate pool depth (typically one meter or deeper) can provide sufficient cover for migrating adults and rearing juveniles. These deep pools are often referred to as holding pools with respect to their function for upstream migrating adults. Pool surface area (m^2) was measured, as was residual pool depth (RPD). RPD is defined as the difference between maximum pool depth and the pool "tail-out" depth, which estimates pool depth at no-flow/drought condition (Figure 11). To be considered a pool, the habitat unit had to meet the criteria described above and had to be of a minimum surface area and depth (RPD). These minimum size criteria are outlined in Table 10. Pool quality is determined using the Pool Quality Index (PQI). The PQI is a "multi-metric" index that was developed for use in the PSL (see Table 11). This index is a modified version of a USFS protocol (*Platts et al*., 1983).

Table 10. *Pool habitat unit criteria (*Schuett-Hames et al.*, 1999b)*

Mean Segment Bankfull Width (m)	**Minimum Unit Size** (m^2)	**Minimum Residual Pool Depth** (m)
0 to < 2.5	0.5	0.10
≥ 2.5 to < 5.0	1.0	0.20
≥ 5.0 to < 10.0	2.0	0.25
≥ 10.0 to < 15.0	3.0	0.30
≥ 15.0 to < 20	4.0	0.35
≥ 20	5.0	0.40

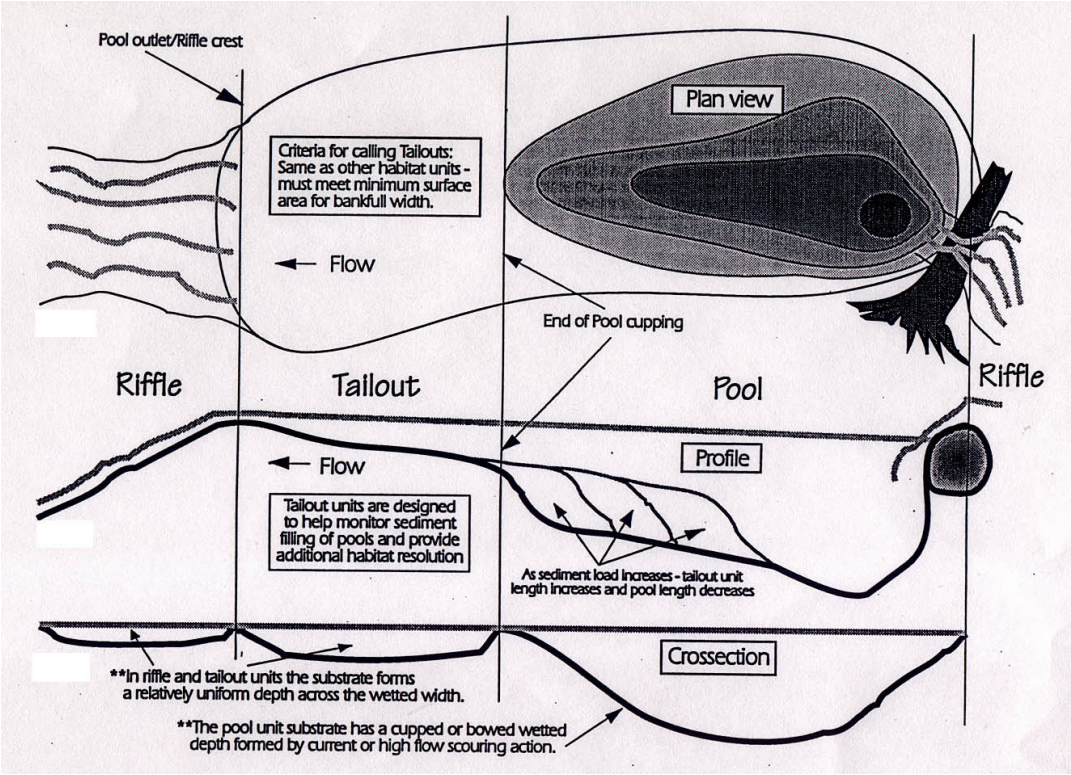

Figure 10. *Pool-riffle habitat units (*Schuett-Hames et al.*, 1999b)*

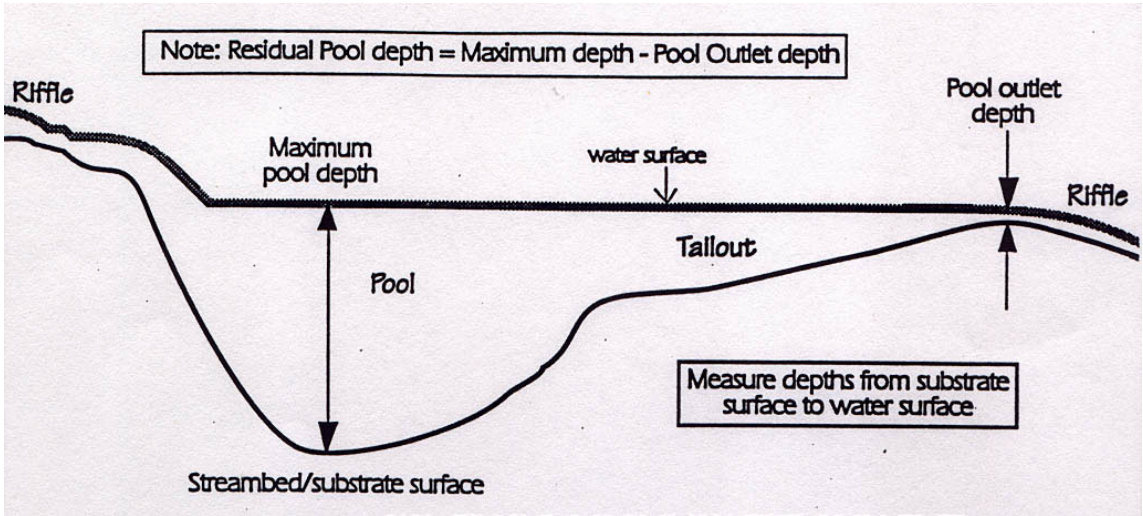

Figure 11. *Residual pool depth (*Schuett-Hames et al.*, 1999b)*

Table 11. *Pool quality index (PQI) for Puget Sound lowland streams (modified from* Platts et al.*, 1983)*

Step	Description	PQI
1A	Maximum pool diameter is approximately = average wetted-width…go to step 2	
1B	Maximum pool diameter is > about one-half average wetted-width…go to step 3	
1C	Maximum pool diameter < about one-half average wetted-width…go to step 4	
2A	Maximum pool depth < 0.5 m…go to step 5	
2B	Maximum pool depth > 0.5 m…go to step 3	
3A	Maximum pool depth > 1 m, regardless of cover conditions, or maximum pool depth > 0.5 m and cover is abundant/excellent	**5**
3B	Maximum pool depth < 0.5 m with, good to excellent cover, or is between 0.5 m and 1 m maximum depth, but has only fair or good cover	**4**
3C	Maximum pool depth < 0.5 m, with only poor to fair cover	**3**
4A	Maximum pool depth > 0.5 m, with good to excellent cover	**3**
4B	Maximum pool depth < 0.5 m, but cover is good to excellent, or maximum pool depth > 0.5 m, but cover is only poor to fair	**2**
4C	Maximum pool depth < 0.5 m, with only poor to fair cover	**1**
5A	Pool cover is good to excellent	**3**
5B	Pool cover is poor to fair	**2**

The types of pool habitat are also recorded in accordance with standard categories (*Bisson et al*., 1982). The following pool types will be utilized in this survey (Figure 12):

- Plunge pool: Formed by scour below a complete or nearly complete channel obstruction (logs, boulders, or bedrock). Substrate is highly variable. Frequently, but not always, shorter than the active channel width.
- Channel pool: Formed by mid-channel scour. Generally with a broad scour hole and symmetrical cross section.
- Lateral scour pool: Formed by flow impinging against one stream bank or partial obstruction (logs, root wad, or bedrock). Asymmetrical cross-section. Includes corner pools in meandering lowland or valley bottom streams.

- Trench pool: Slow flow with U or V-shaped cross section typically flanked by bedrock walls. Often very long and narrow with at least half of the substrate comprised of bedrock or hard-pan material.
- Dam pool: Water impounded upstream of channel blockage (e.g., LWD debris jams or landslides).
- Beaver dam pool: Dammed pool formed specifically by beaver activity.
- Backwater pool: Found along channel margins; created by eddies around obstructions such as boulders, root wads, or woody debris. Part of active channel at most flows; scoured at high flow. Substrate typically composed of sand, gravel, and cobble.

From these field surveys, the following parameters were determined:

- Pool frequency (# pools/km)
- Pool-spacing (in terms of BFW)
- Pool area per km and average pool area (m^2)
- Mean residual pool depth (RPD)
- Pool habitat (% of total stream surface area)
- Pool quality index (PQI)
- Pool diversity (types of pools present)

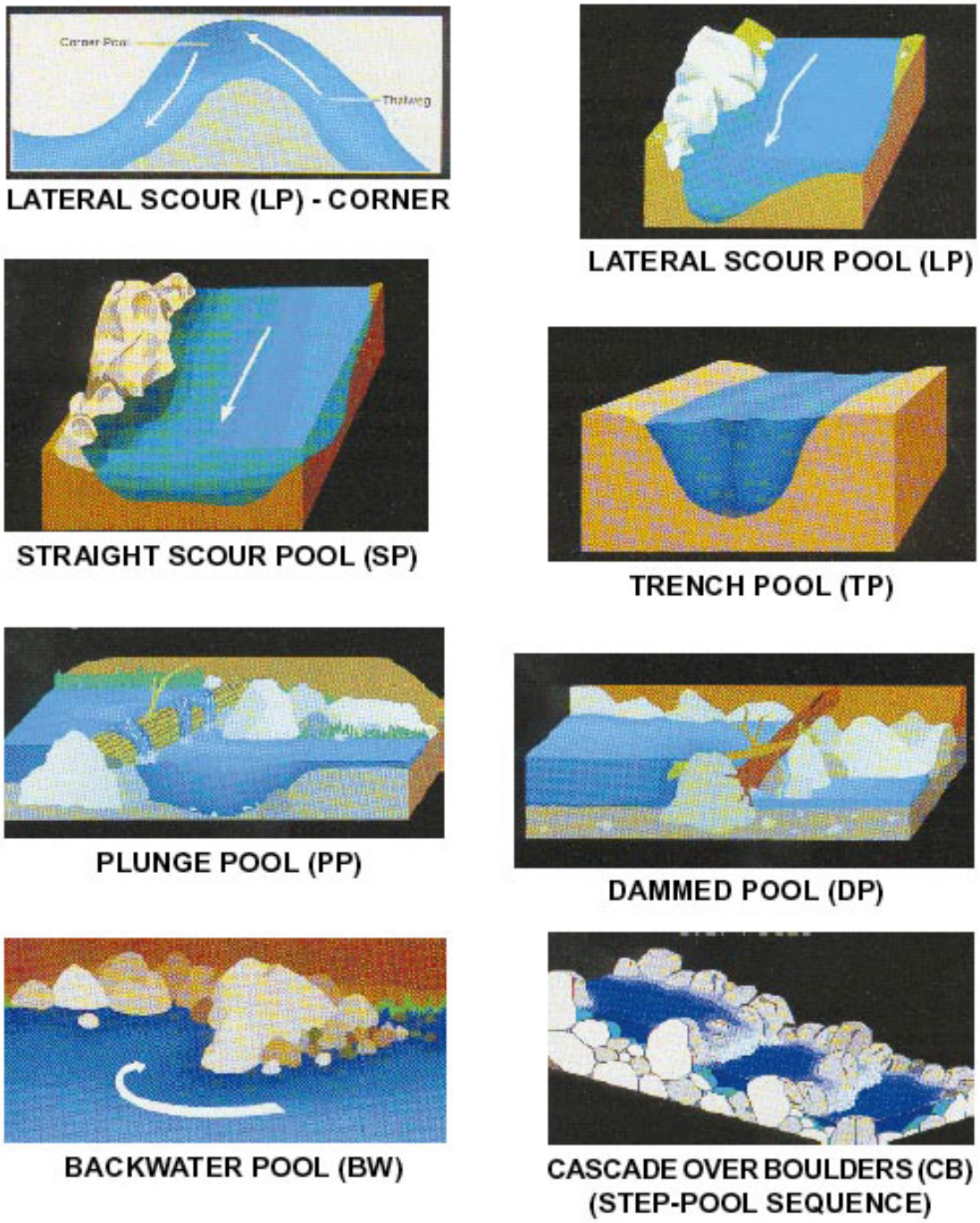

Figure 12. Rearing habitat unit types (*Bisson et al*., 1982)

Salmonid Spawning Habitat

Riffle and pool tail-out surface area was measured and used to determine the quantity of spawning habitat within the survey reach (% riffles by surface area). The primary measure of spawning habitat quality utilized in this study was the streambed condition. Riffle substrata composition was assessed based on particle size distribution (dominant and sub-dominant particle size) and embeddedness (Figure 13). For each riffle habitat unit, particle size was simply estimated as boulder, cobble, gravel, sand, or silt.

Streambed substrata size is one of the most important determinants of benthic habitat character for fish and macroinvertebrates in streams. Along with bed-form (e.g. riffles, glides, and pools), substrate influences the hydraulic roughness and consequently the range of the water velocities in the channel. It also influences the size range of interstices that provide living space and cover for macroinvertebrates, salamanders, and benthic-dwelling fish (sculpins and juvenile salmonids). Sediment characteristics are often sensitive indicators of the effects of human activities on streams. Decreases in the mean sediment size, increases in the percentage of fine sediments, and/or substrata embeddedness may significantly reduce spawning habitat or destabilize channels (*Chapman*, 1988). These parameters also may indicate changes in the rates of upland erosion and sediment supply in the drainage basin as a whole. Fine sediment tends to fill pools and degrade spawning gravel quality (*Chapman*, 1988). An overall increase in fine sediment composition can negatively effect the aquatic ecosystem integrity (*MacDonald et al.*, 1991). In this protocol, substrate size was evaluated using a modification of procedures first described by *Wolman* (1954). In addition to estimating the particle size distribution, the quality of the riffle was rated using a RQI developed for use in the PSL (see Table 12).

The following types of habitat units were also identified during this phase of the stream assessment process (Figure 14):

- Riffle: Fast, turbulent, shallow flow over submerged or partially submerged gravel and cobble substrates. Generally broad, uniform cross section. Low gradient, usually < 4% slope, rarely up to 6%.
- Riffles with pocket-water: Same flow and gradient as riffle but with numerous small sized pools or "pockets" created by scour associated with small boulders, wood, or gravel-bars and ridges.
- Rapids: Also referred to as high-gradient riffles. Swift, turbulent flow including chutes and some hydraulic jumps swirling around boulders. Exposed substrate composed of individual boulders, boulder clusters, and cobble-bars. Moderate gradient, usually 2–4% slope, occasionally > 6%.
- Cascades: Much of the exposed substrate composed of boulders and/or cobbles organized into clusters, partial bars, or step-pool sequences. Fast, turbulent, flow; many hydraulic jumps, strong chutes, and eddies; a majority of white water or rapids. High gradient, usually 4–10% slope, sometimes greater. May form a natural impassable barrier to anadromous salmonid migration, but many are passable if flow conditions are suitable and LWD forms step-pools allowing temporary fish passage upstream.

- Hyporheic zone: Dry section of stream separating wetted channel units. Typical examples are riffles with subsurface flow or portions of side channels separated by large isolated pools. Record the length, active channel width, and all other variables for the dry areas.
- Dry channel: Section of the main channel or side channel that is completely dry at time of survey. Not surveyed for this protocol.
- Glide: An area with generally uniform depth and flow with no surface turbulence. Low gradient, < 2% slope. Glides may have some small scour areas but are distinguished from pools by their overall homogeneity and lack of structure, cover or complexity. Generally deeper than riffles with few major flow obstructions and low habitat complexity. Often remnants of channelized sections of the creek created for agricultural land-use of flood-control activities. Very common in urbanized areas due to stormwater run-off, and frequent high-flow scour events. Glides provide little, if any salmonid rearing or spawning habitat.

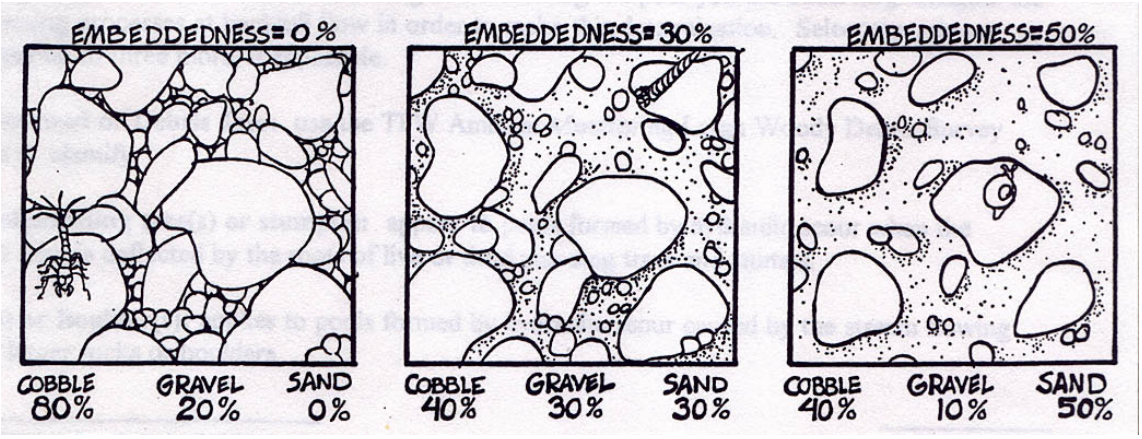

Figure 13. *Streambed embeddedness (*Schuett-Hames et al.*, 1999e)*

Table 12. *Riffle quality index (RQI) for Puget Sound lowland streams*

Step	Description	RQI
1A	Riffle substrata is a mixture of cobble and gravel, with little sand or silt (low embeddedness) and streambed is relatively stable, with little evidence of scour or deposition (i.e. exposed bed or fresh gravel-bars)…go to step 2	
1B	Riffle substrata consists mostly of gravel, with some sand/silt (moderate embeddedness) or some evidence of moderate streambed instability (scour or deposition)…go to step 3	
1C	Riffle substrata consists mostly of sand and silt, with some gravel (high embeddedness), or some evidence of severe instability…go to step 4	
2A	Pool tail-out at head of riffle or riparian wetland within 10 m of riffle, and abundant/excellent-quality cover on riffle	**5**
2B	Pool tail-out at head of riffle or riparian wetland within 10 m of riffle and poor to good-quality cover on riffle, or glide or run upstream of riffle, no wetland within 10 m upstream, and abundant to excellent-quality cover on riffle	**4**
2C	Glide or run upstream of riffle, no wetland within 10 m upstream, and little or no cover on riffle	**2**
3A	Pool tail-out at head of riffle, riparian wetland within 10 m of riffle, or pool just downstream of riffle or abundant/excellent-quality cover on riffle	**4**
3B	Glide or run upstream of riffle, no wetland within 10 m upstream, and no pool downstream of riffle and moderate/good-quality cover on riffle	**3**
3C	Glide or run upstream of riffle, no wetland within 10 m upstream, and no pool downstream of riffle and little or no cover on riffle	**2**
4A	Pool tail-out at head of riffle, riparian wetland within 10 m of riffle, or pool just downstream of riffle and good-excellent cover on riffle	**2**
4B	Glide or run upstream of riffle, no wetland within 10 m upstream, and no pool downstream of riffle or poor-fair cover on riffle	**1**

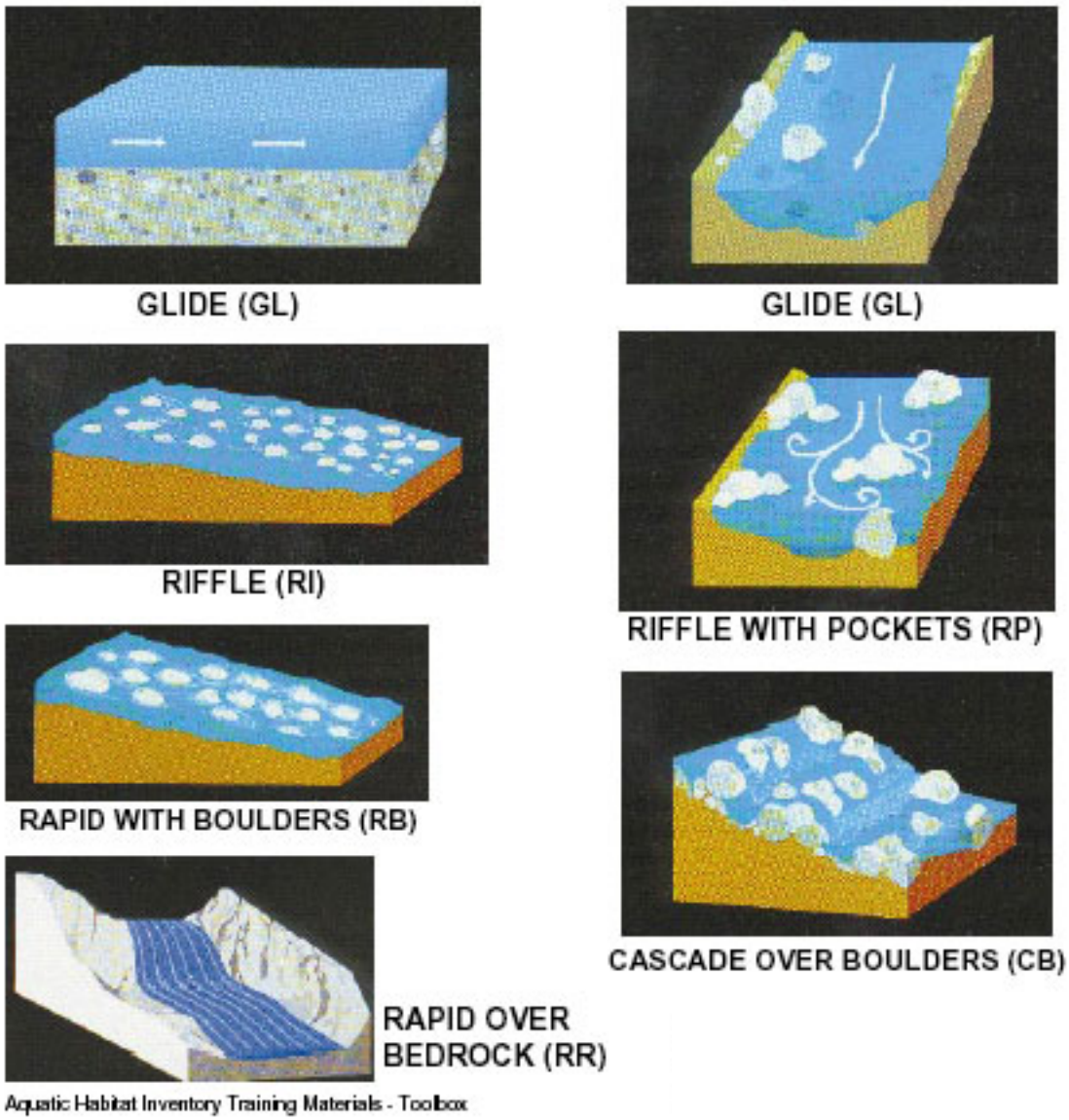

Figure 14. *Spawning habitat unit types (*Bisson et al.*, 1982)*

Large Woody Debris Measurements

LWD is a vital structural and functional component of streams in the PNW. LWD influences channel morphology and fish habitat in the formation and maintenance of pools, trapping and storing fine sediment, and dissipating flow energy. LWD also provides cover for instream biota. The effectiveness of LWD is related to the size, stability, location, and longevity of individual pieces and debris jams. LWD is the key component in maintaining a high degree of spatial heterogeneity or habitat complexity (*Maser et al*., 1988). Perhaps no other structural component is as important to salmonid habitat as is LWD. LWD is a ubiquitous component in streams of the PNW. LWD performs critical functions in forested lowland streams, including dissipation of flow

energy, streambank protection, streambed stabilization, sediment storage, and providing instream cover and habitat diversity (*Harmon et al*., 1986; *Bisson et al*., 1987; *Gregory et al*., 1991).

Although the influence of LWD may change over time, both functionally and spatially, its overall importance is significant and persistent. LWD causes a variety of physical and hydraulic changes to occur in the stream channel. These inchannel interactions can vary considerably depending on the channel gradient and type. Biological changes typically follow the physical changes (*Harmon et al*., 1986). The physically-induced biological influences of LWD are substantial. Fish populations have been shown to decline rapidly following LWD removal (*Bryant*, 1983; *Hicks et al*., 1991). LWD in low-gradient pool-riffle or plane-bed streams found in this region has the greatest range of functional influences (*Bilby and Ward*, 1989 and 1991). *Keller and Swanson* (1979) found that LWD sediment storage in low-gradient stream channels was significant. Streambank protection and streambed stability are also controlled by LWD abundance and distribution in forested streams of this region (*Bilby*, 1984). Hydraulic roughness can increase by more than 50% due to disruption of flow by individual pieces of LWD or debris jams (*Smith et al*., 1993). Creation of high-flow refugia is also an important function of LWD. Pool formation in particular can be almost completely determined by the quantity and distribution of LWD in forested streams. Pool frequency has been shown to be directly proportional to LWD frequency and pool depth, surface area, and cover-quality are also directly related to LWD quantity and quality (*Andrus et al*., 1988; *Robison and Beschta*, 1990; *Ralph et al*., 1994). In general, small natural stream channels in the PNW tend to contain an abundance of LWD (*Naiman and Bilby*, 1998).

Watershed development can significantly affect both the quantity and quality of LWD in streams (*May et al*., 1997). Few studies have specifically quantified LWD in urbanizing streams and therefore most comparative data comes from studies of forested streams in the PNW. Nevertheless, the importance of LWD and its functional role in streams in urbanizing watersheds of the PSL is very much the same as it is in streams draining undisturbed, native forests.

Methods for large woody debris (LWD) measurement are based on a simplified version of the methodology described by *Beschta and Robison* (1990) and *Shuett-Hames et al*. (1999). This component of the physical habitat assessment protocol allows quantitative estimates of the number, type (coniferous or deciduous), size/volume, decay-class, and distribution of wood within the stream reach. All pieces of LWD that are at least partially in the active channel or spanning above the active channel are tallied and measured (Figures 14 and 15). LWD in the active channel is tallied continuously over the entire length of the survey reach. Zones are in the wetted channel (1), within the bankfull channel (2), spanning the bankfull channel (3), or outside the active channel, but within the floodplain area (4).

For this protocol, LWD is defined as logs at least 2 m (6 ft) long and at least 15 cm (6 in) diameter (*Peterson et al*. 1992) or root-wads of any size (estimated to nearest 0.05 meter). For each LWD piece, its length and diameter are measured. Sometimes LWD is not cylindrical, so it has no clear diameter. Here an estimate is made of what the diameter would be for a piece of wood with a circular cross-section that would have the same volume. When evaluating length, only the part of the LWD piece that has a

diameter greater than 15 cm is measured. The diameter on the field form refers to the large end diameter. Each of the LWD pieces was one entry and the whole piece was included when assessing dimensions (Figures 15 and 16).

So-called key pieces of LWD are those that are very large and therefore very stable within the stream channel. For most PSL streams, LWD greater than 0.5 m (1.5 ft) in diameter and longer than 5 m (15 ft) are considered to be key pieces. For this protocol, all LWD is tallied, but key pieces are noted as a unique feature during the data analysis process.

The classification of LWD includes wood-type (coniferous, deciduous, or man-made), the decay condition (solid, moderate decay, or rotten), and the stability of the piece (rooted, buried, pinned, or unstable). Debris jams that contain multiple pieces of LWD should be noted with an estimate of the number of pieces and average size of LWD (Figure 17). Artificial log weirs and deflectors comprised a portion of LWD in many urban streams and should be identified as such.

Values should be obtained for each of the following LWD characteristics:

- LWD frequency (# LWD pieces per kilometer)
- Key LWD (# key LWD pieces per kilometer)
- LWD frequency (BFW spacing)
- LWD volume (cubic meters per kilometer)
- Mean LWD volume (per survey reach)
- Number of key pieces of LWD (diameter > 0.5 meters)
- Percentage of pools formed by LWD
- LWD quality (position, species, and decomposition)

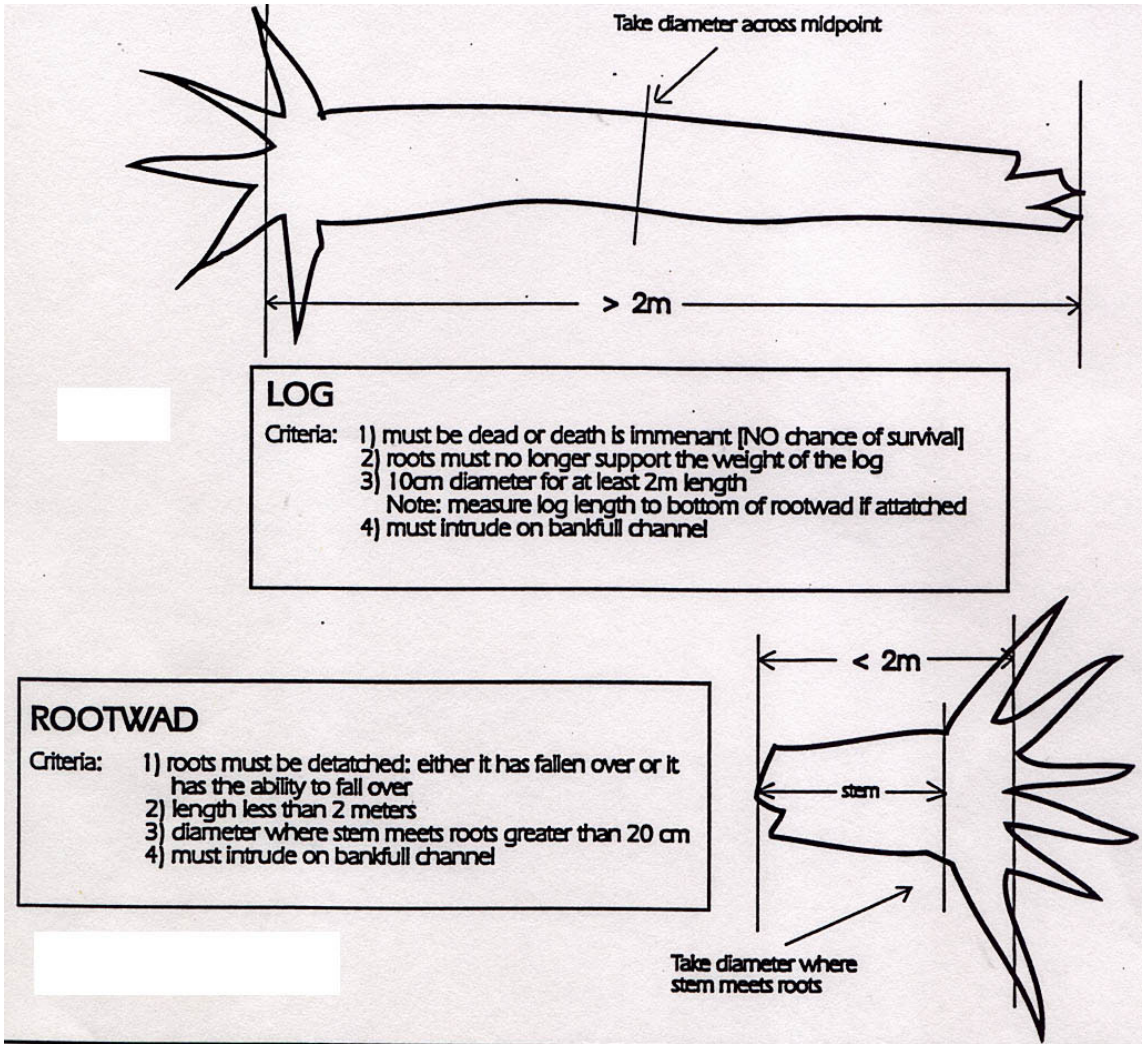

Figure 15. *Large woody debris (LWD) measurement key (*Schuett-Hames et al.*, 1999a)*

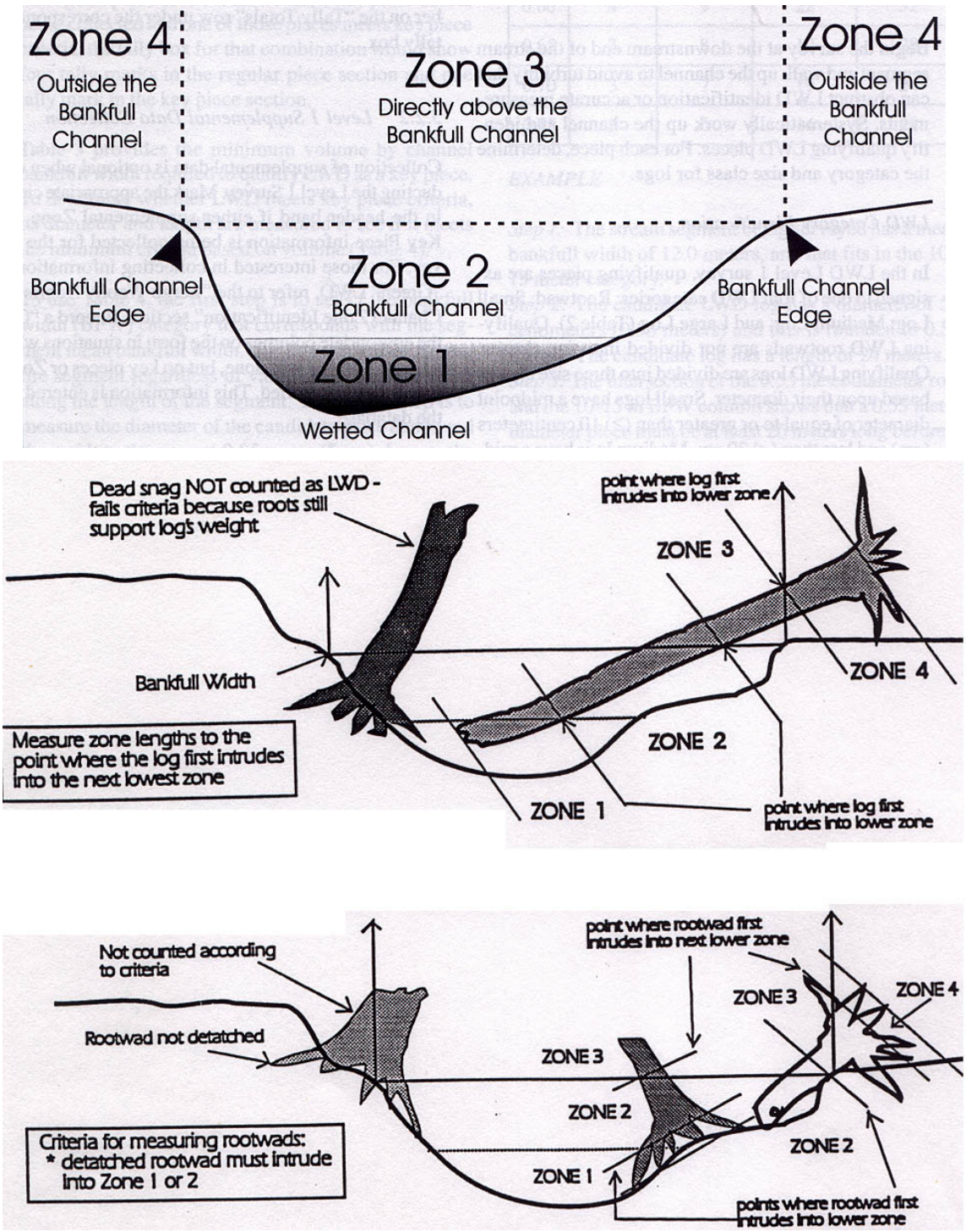

Figure 16. *Large woody debris (LWD) position key (*Schuett-Hames et al.*, 1999a)*

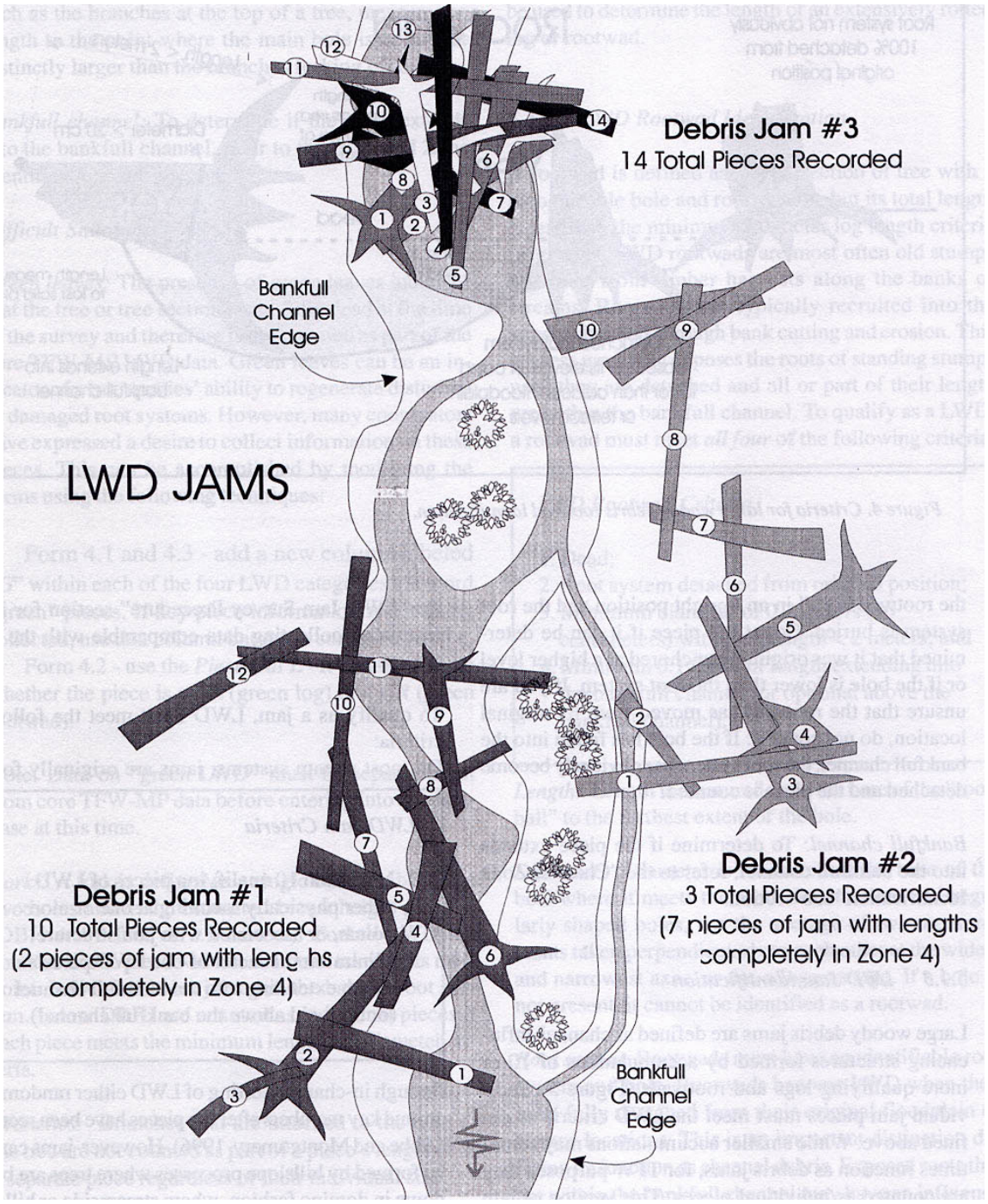

Figure 17. *Large woody debris (LWD) jam (*Schuett-Hames et al.*, 1999a)*

Summary of Stream Habitat Assessment Protocols

Stream channel geomorphology and instream physical habitat structure are determined largely by the fluvial dynamics of the stream system (*Leopold et al*., 1964; *Dunne and Leopold*, 1978; *Lisle*, 1979; *Poff et al*., 1997; *Naiman and Bilby*, 1998). These fluvial dynamics are, in turn, dictated by the natural processes and land-use activities occurring within the watershed of the stream system (*Leopold*, 1980; *Swanson et al*., 1990; *Bisson et al*., 1992; *Stanford and Ward*, 1992; *Naiman and Bilby*, 1998). Therefore these watershed processes can directly and indirectly affect the stream-riparian ecosystem habitat structure and the populations of aquatic biota as well. This is one of the main justifications for measurement of physical habitat characteristics. However, monitoring activities can focus too heavily on the structural component of habitat and may ignore the underlying processes responsible for habitat formation and maintenance (*Poole et al*., 1997). Adequate, high-quality habitat is essential for healthy salmonid populations, but habitat structure alone is not sufficient. A functional watershed is the key to long-term maintenance of habitat that supports all components of the ecosystem. This requires a more holistic approach to watershed management where critical processes are supported and maintained through good land stewardship and resource conservation. This includes processes such as the natural hydrologic regime, sediment delivery and transport mechanisms, LWD recruitment, and natural stream-riparian interactions. Instream habitat assessment, water quality monitoring, and biological monitoring are just a few of the management activities necessary to maintain a healthy watershed, stream system, and salmonid population.

Monitoring ecosystem components (physical, chemical, and biological) that provide data to link cause (watershed land-use) and effect (streambank erosion, streambed sedimentation, depletion of LWD, loss of pool habitat, etc.) should be the goal of an effective monitoring program. Too heavy a focus on instream habitat structure can result in "band-aid" management and rehabilitation that does not address the functional problems that have caused the degradation of habitat (e.g., LWD installation without addressing hydrologic problems upstream). A holistic approach to monitoring, such has been outlined here, that addresses all the biophysical aspects of stream ecosystem dynamics is the recommended approach.

This protocol is fully compatible with habitat assessment methods recommended for use in urbanizing watersheds of the PSL (*Scholz and Booth*, 2001). This protocol relies heavily on the techniques described in the TFW ambient monitoring manuals (see Table 11) that are currently recognized as the standard habitat assessment methods for use in the region. Table 14 contains the standard field data sheets recommended for use with this protocol.

It is recommended that the following periodicity be followed for each of the components of this protocol:

- GIS-based watershed assessment – every 3-5 years
- Biological monitoring (B-IBI) – every 1-2 years
- Fish surveys – annually
- Physio-chemical WQ monitoring – monthly

- Instream habitat assessment – every 3-5 years

Table 13 contains a summary of key habitat parameters and target conditions that reflect the optimal range for each parameter, based on natural conditions in reference streams. This table should be used only as a guide for rating streams during baseline surveys, or for setting rehabilitation/restoration goals.

Table 13. *Summary of TFW ambient monitoring protocols applicable to stream assessment in the PNW*

Protocol Name	Protocol Citation
1. TFW Method Manual for the Large Woody Debris Survey	Shuett-Hames, D., A. E. Pleus, J. Ward, M. Fox, and J. Light. 1999a. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-004. DNR #106. March. 33 pp.
2. TFW Method Manual for the Habitat Unit Survey	Pleus, A. E., D. Shuett-Hames, and L. Bullchild. 1999b. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-003. DNR #105. June. 31 pp.
3. TFW Method Manual for the Salmonid Spawning Gravel Composition Survey	Shuett-Hames, D., R. Conrad, A. Pleus, and M. McHenry. 1999c. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-001. DNR #101. March. 48 pp.
4. TFW Method Manual for the Salmonid Gravel Scour Survey	Shuett-Hames, D., A. E. Pleus, and D. Smith. 1999d. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-008. DNR #110. December. 41 pp.
5. TFW Method Manual for the Salmonid Spawning Habitat Availability Survey	Shuett-Hames, D., A. E. Pleus, and D. Smith. 1999e. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-007. DNR #119. November. 32 pp.
6. TFW Method Manual for the Reference Point Survey	Pleus, A. E., D. Shuett-Hames. 1998a. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-008. DNR #002. May. 31 pp.
7. TFW Method Manual for Wadable Stream Discharge Measurement	Pleus, A. E. 1999a. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-009. DNR #111. June. 13 pp.
8. TFW Method Manual for the Stream Temperature Survey	Pleus, A. E. 1999b. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-005. DNR #107. June. 35 pp.
9. TFW Method Manual for Stream Segment Identification	Pleus, A. E., D. Schuett-Hames. 1998b. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-98-001. DNR #103. May. 39 pp.
10. TFW Riparian Stand Survey	Smith, D. 1998. Northwest Indian Fisheries Commission. Olympia, WA. September. 12 pp.

Table 15. *Salmonid habitat condition ratings (*NMFS & WCC*, 1999)*

Habitat Factor	PARAMETER/ UNIT	Channel Type	Poor	Fair	Good	Source
Access and Passage						
Artificial Barriers	% known or potential habitat blocked by artificial barriers	All	>20%	10-20%	<10%	WCC
Floodplains						
Floodplain Connectivity	Stream and off-channel habitat length with lost floodplain connectivity due to incision, roads, dikes, flood protection, or other	<1% gradient	>50%	10-50%	<10%	WCC
Loss of Floodplain Habitat	Lost wetted area	<1% gradient	>66%	33-66%	<33%	WCC

Table 15 (continued). *Salmonid habitat condition ratings (*NMFS & WCC*, 1999)*

Channel Conditions						
Fine Sediment	Fines < 0.85 mm in spawning gravel	All – Westside	>17%	11-17%	≤11%	WSP/WSA / NMFS/Hood Canal
	Fines < 0.85 mm in spawning gravel	All – Eastside	>20%	11-20%	≤11%	NMFS
Large Woody Debris	#pieces/m of channel length	≤4% gradient, <15 m wide (Westside only)	<0.2	0.2-0.4	>0.4	Hood Canal/Skagit
	or use Watershed Analysis piece and key piece standards listed below when data are available					
	pieces/channel width	<20 m wide	<1	1-2	2-4	WSP/WSA
	key pieces/channel width*	<10 m wide (Westside only)	<0.15	0.15-0.30	>0.30	WSP/WSA
	key pieces/channel width*	10-20 m wide (Westside only)	<0.20	0.20-0.50	>0.50	WSP/WSA

* Minimum size to qualify as a key piece:	BFW (m)	Diameter (m)	Length (m)
	0-5	0.4	8
	6-10	0.55	10
	11-15	0.65	18
	16-20	0.7	24

Table 15 (continued). *Salmonid habitat condition ratings (*NMFS & WCC*, 1999)*

Percent Pool	% pool, by surface area	<2% gradient, <15 m wide	<40%	40-55%	>55%	WSP/WSA
	% pool, by surface area	2-5% gradient, <15 m wide	<30%	30-40%	>40%	WSP/WSA
	% pool, by surface area	>5% gradient, <15 m wide	<20%	20-30%	>30%	WSP/WSA
	% pool, by surface area	>15 m	<35%	35-50%	>50%	Hood Canal
Pool Frequency	channel widths per pool	<15 m	>4	2-4	<2	WSP/WSA
	channel widths per pool	>15 m	-	-	channel width / pools/ mile / cw/ pool 50' / 26 / 4.1 75' / 23 / 3.1 100' / 18 / 2.9	NMFS
Pool Quality	#pools >1 m deep with good cover and cool water	All	No deep pools and inadequate cover or temperature, major reduction of pool volume by sediment	Few deep pools or inadequate cover or temperature, moderate reduction of pool volume by sediment	Sufficient deep pools	NMFS/WSP/WSA
Streambank Stability	% of banks not actively eroding	All	<80% stable	80-90% stable	>90% stable	NMFS/WSP

Table 15 (continued). *Salmonid habitat condition ratings (*NMFS & WCC*, 1999)*

Sediment Input						
Sediment Supply	$m^3/km^2/yr$	All	> 100 or exceeds natural rate*	-	< 100 or does not exceed natural rate*	Skagit
	* Note: this rate is highly variable in natural conditions					
Mass Wasting		All	Significant increase over natural levels for mass wasting events that deliver to stream	-	No increase over natural levels for mass wasting events that deliver to stream	WSA
Road Density	mi/mi^2	All	>3 with many valley bottom roads	2-3 with some valley bottom roads	<2 with no valley bottom roads	NMFS
	or use results from Watershed Analysis where available					

Table 15 (continued). *Salmonid habitat condition ratings (*NMFS & WCC*, 1999)*

Riparian Zones						
Riparian Condition	• riparian buffer width (measured out horizontally from the channel migration zone on each side of the stream) • riparian composition	Type 1-3 and un-typed salmonid streams >5' wide	• <75' or <50% of site potential tree height (whichever is greater) OR • Dominated by hardwoods, shrubs, or non-native species (<30% conifer) unless these species were dominant historically.	• 75'-150' or 50-100% of site potential tree height (whichever is greater) AND • Dominated by conifers or a mix of conifers and hardwoods (≥30% conifer) of any age unless hardwoods were dominant historically.	• >150' or site potential tree height (whichever is greater) AND • Dominated by mature conifers (≥70% conifer) unless hardwoods were dominant historically	WCC/WSP
	• buffer width • riparian composition	Type 4 and un-typed perennial streams <5' wide	<50' with same composition as above	50'-100' with same composition as above	>100' with same composition as above	WCC/WSP
	• buffer width • riparian composition	Type 5 and all other un-typed streams	<25' with same composition as above	25'-50' with same composition as above	>50' with same composition as above	WCC/WSP

Table 15 (continued). *Salmonid habitat condition ratings (*NMFS & WCC*, 1999)*

Water Quality						
Temperature	degrees Celsius	All	>15.6° C (spawning) >17.8° C (migration and rearing)	14-15.6° C (spawning) 14-17.8° C (migration and rearing)	10-14° C	NMFS
Dissolved Oxygen	mg/L	All	<6	6-8	>8	ManTech
Hydrology						
Flow	hydrologic maturity	All	<60% of watershed with forest stands aged 25 years or more	-	>60% of watershed with forest stands aged 25 years or more	WSP/Hood Canal
		or use results from Watershed Analysis where available				
	% total impervious surface area (%TIA)	Lowland basins	>10%	3-10%	≤3%	Skagit
Biological Processes						
Nutrients (Carcasses)	Number of stocks meeting escapement goals	All anadromous	Most stocks do not reach escapement goals each year	Approximately half the stocks reach escapement goals each year	Most stocks reach escapement goals each year	WCC

PROJECT FINDINGS

Data from the watershed analysis, bio-monitoring, and instream habitat assessment phases of the project are presented in this section of the report. Data highlights are presented in bulleted lists for each military installation, with more detailed data in the report appendices.

Watershed Analysis

Results of the GIS analysis of each stream sub-basin are summarized in Table 16. The range of watershed development found on PNW military installations generally mirrored the range found in the Puget Sound region as a whole. Using % TIA (Table 23) as a gross measure of watershed development, the range of landscape alterations within each base can be seen. In general, research in the PSL eco-region (*May et al*., 1997; *Horner and May*, 1999; *Booth et al*., 2001) indicates that potentially significant hydrologic and ecological changes in aquatic ecosystem integrity occur as watershed development increases above the 5–10% TIA range. There is no real threshold of change that occurs. It is more of a continuous decline in natural ecological integrity. The loss of natural vegetative (forest and prairie) cover is one of the most significant factors in these changes, especially the shift in hydrologic regime (Figures 1 and 2). In addition to the negative impacts of imperviousness, regional studies (*May et al*., 1997; *Horner and May*, 1999; *Booth et al*., 2001) also indicate that when basin forest cover is reduced below the 70–80% range, stormwater run-off problems tend to become a major problem. Along with other changes, non-point source (NPS) pollution also becomes a factor that must be dealt with at this level of watershed land-cover and land-use change. As part of each individual military base summary, the implications of these land-cover and land-use issues will be presented.

Biological Monitoring Data Analysis

The Benthic Index of Biotic Integrity (B-IBI) used in this study as the primary measure of biological health of the stream systems is composed of ten metrics of taxa richness and diversity, population attributes, disturbance tolerance, and functional feeding groups. For a given invertebrate attribute to be included as a metric in the B-IBI, it must respond predictably along a gradient of anthropogenic disturbance (*Kerans and Karr*, 1994; *Kleindl*, 1995; *Fore et al*., 1996; *Karr and Chu*, 1999; *Morley*, 2000). This relationship was extensively tested in the Puget Sound region (*Kleindl*, 1995; *May et al*., 1997; *Dewberry et al*., 1999; *Horner and May*, 1999; *Morley*, 2000; *Booth et al*., 2001). When values from the ten metrics are combined, B-IBI scores can range from a minimum of 10 to a maximum of 50.

The results of the SERDP Puget Sound military base bio-monitoring efforts are shown in Figures 18 and 19. Figure 18 show the B-IBI scores for all sample sites. Figure 19 show the scores in relation to the five classifications of biological condition or levels of stream health. Figure 18 shows B-IBI scores in relation to overall watershed urbanization or development level. This is expressed in terms of the total percentage of the watershed that is covered by impervious surfaces (% TIA). Studies in the Puget Sound region and elsewhere in the country have displayed this characteristic relationship between human influence on a watershed scale and the level of degradation of aquatic ecosystems. Figure

21 shows the SERDP bio-monitoring data plotting along with the existing PSL B-IBI database (1997–2000 bio-monitoring data). A detailed discussion of each of these figures and the significance of this data with respect to watershed management follows and is also included in each installation summary section.

A majority (75%) of the sites sampled during the Puget Sound SERDP military base bio-monitoring effort scored in the "fair-good" range (Figure 19). The remaining sites (25%) were rated as "poor", with no sites in the "very poor" category. This is likely a reflection of the generally low-development level found in most military installation watersheds. While development has certainly impacted the aquatic ecosystems within the military installations of the Puget Sound region, the level of development has not yet reached the level where water resources are severely degraded, except in a few locations where intense development levels are present due to unique military operations (e.g., Clover Creek on McChord AFB, where the main runway and flight-line is within the stream corridor). On the other hand, no sites were rated as "excellent" or what is generally considered to be a natural, reference condition. The sites rated as "good" were all in sub-basins with little development and all contained relatively intact riparian corridors and wetland areas. Details on stream biological integrity in each DoD installation can be found in the individual installation summary sections to follow.

In comparing the B-IBI scores from the Puget Sound SERDP military base bio-monitoring effort with the existing PSL database it can be seen that there is a very close "fit" between these two independent data sets (Figure 21). The PSL database represents a number of watersheds from the region over a range of development levels. In general, most of the DoD sample sites appear to be clustered in the lower tier of development found in the PSL eco-region. A few highly developed sites are also present in the DoD dataset (e.g., Clover Creek on McChord AFB), but these sites are also well within the expected level of biological integrity found in highly urbanized streams.

Of particular interest are the Muck and Murray Creek sites highlighted in Figure 21. These sites appear to have much lower B-IBI scores than would be predicted based solely on the level of watershed development in their sub-basins. A possible explanation for this apparent contradiction may be that these sites are all located within the South Puget Sound Prairie (SPSP) ecosystem. Little is known about streams in this unique ecosystem (see Appendix D for a summary of the SPSP ecosystem) and therefore, the standard B-IB scores used for forested watersheds may not reflect native conditions in these stream systems. One other possible mitigating factor for better or worse biological integrity is the condition of the riparian forest both on a watershed and local scale in relation to the bio-monitoring site. Research in the PNW has shown that riparian forests can have a significant influence on stream health (*May and Horner*, 2000) and that local stream corridor conditions can also affect biological integrity.

It is clear from the data gathered as part of the Puget Sound SERDP military base bio-monitoring effort and corresponding data from the PSL region, that the cumulative effects of watershed development have impacted the biological integrity or health of the freshwater streams in this region. Some general conclusions can be drawn from previous research and from these results (*May et al.*, 1997; *Horner and May*, 1999; *Horner and May*, 2001):

- The very highest biological indices in all cases are at extremely low values of watershed development, meaning that the best ecological health is impossible unless human presence is very low and the natural vegetation and soil systems are well preserved near streams and throughout watersheds.
- Biological responses to watershed development in combination with loss of natural cover do not indicate thresholds of watershed change that can be absorbed with little decline in health.
- Relatively high levels of biological integrity cannot occur without comparatively low urbanization and an intact natural landscape. However, these conditions do not guarantee fairly high integrity and should be regarded as necessary but not sufficient conditions for its occurrence. In contrast, comparatively high urbanization and natural cover loss make relatively poor biological health inevitable.
- The standard B-IBI protocols and bio-monitoring analysis methods may not be appropriate for unique ecosystems such as the South Puget Sound Prairie.

Table 16. *Land-use and land-cover data for Puget Sound DoD study watersheds*[1]

Watershed	Total Impervious Area (%TIA)	Native Forest	Native Grass	Bare Soil	Urban Forest	Urban Grass	Urban Paved
Fort Lewis							
Lower Muck Creek[2]	**20**	38.5	26.8	0.1	23.2	8.1	3.3
Upper Muck Creek[2]	**29**	31.4	21.4	0.6	24.3	15.9	6.5
Muck Creek[3]	**19**	35.0	25.0	0.5	24.5	11.0	4.0
Murray Creek	**36**	20.3	11.0	1.1	47.2	12.1	8.4
Lacamus Creek	**19**	44.5	22.0	0.5	22.5	8.0	2.5
Sequalitchew Creek	**36**	25.8	8.9	1.3	42.8	11.1	10.2
McChord AFB							
Lower Clover Creek[4]	**60**	4.5	16.6	2.2	13.1	35.7	27.8
Upper Clover Creek[4]	**42**	15.5	19.2	1.9	25.3	30.3	7.7
Morey Creek	**38**	17.6	12.4	0.7	41.5	21.3	5.1
NSB Bangor							
Devils Hole Creek	**27**	54.8	6.5	0.3	11.5	19.8	7.1
Cattail Creek	**11**	78.0	5.4	0.0	12.0	4.5	0.1
NCS Jim Creek							
Jim Creek	**10**	77.0	4.5	0.0	15.7	2.3	0.5
Cub Creek	**8**	80.0	3.0	0.0	12.0	3.0	2.0

Notes: (1) All values are in percent (%) unless otherwise noted. Data is based on University of Washington Center for Urban Water Resources Management land-use and land-cover database (http://depts.washington.edu/cuwrm/research/landsat.htm).

(2) Upper and Lower Muck Creek watershed boundary is at Roy.

(3) Muck Creek on Fort Lewis includes Johnson and Lacamus tributaries.

(4) Upper and Lower Clover Creek watershed boundary is at McChord runway.

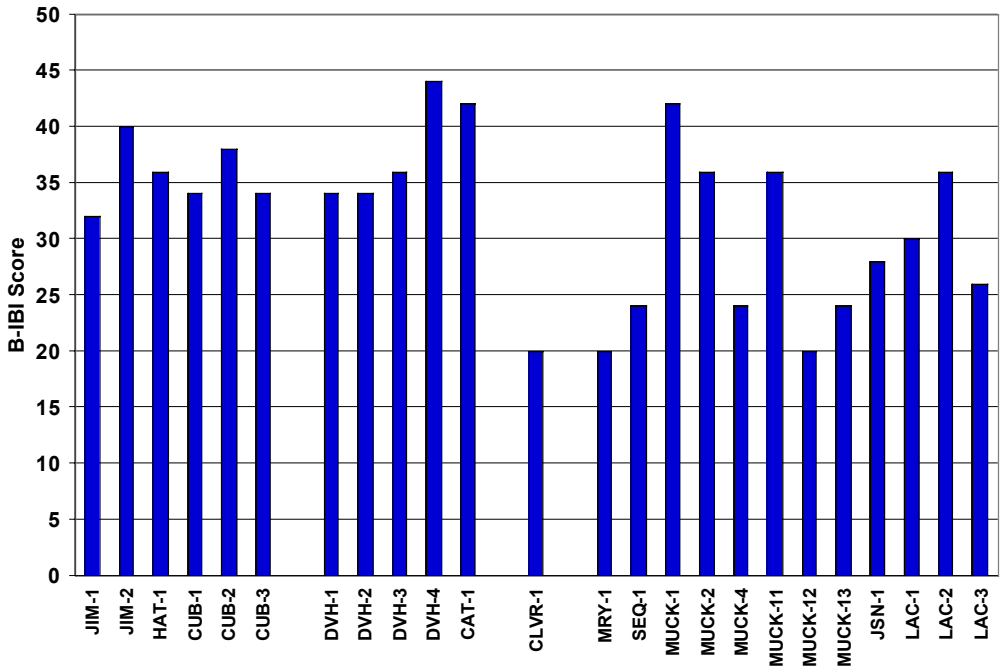

Figure 18. *Benthic Index of Biotic Integrity (B-IBI) scores for streams in the Puget Sound SERDP military base assessment project*

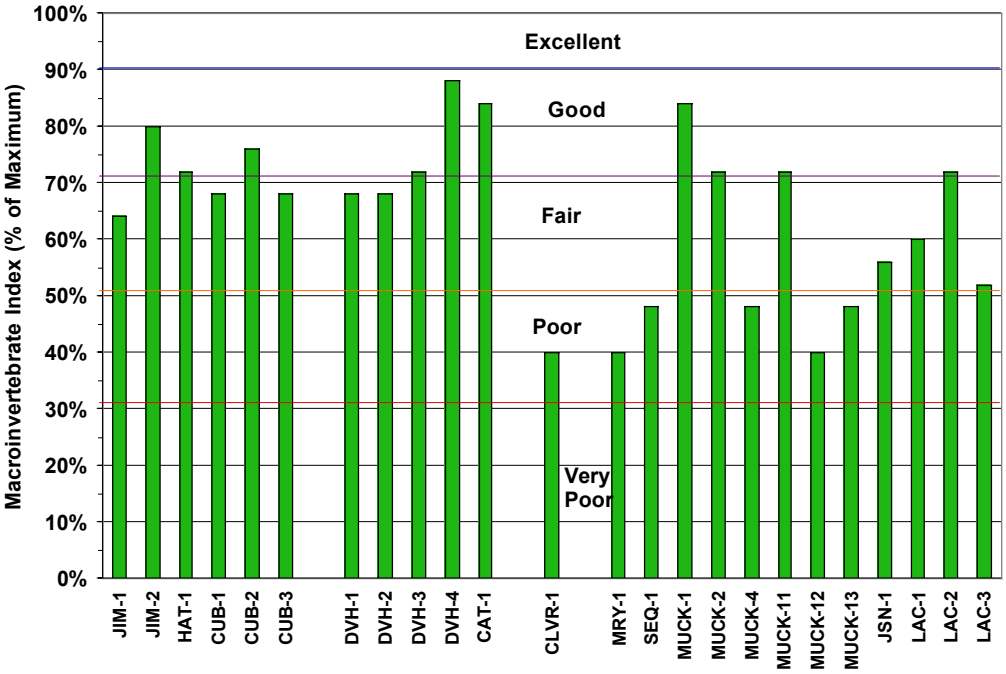

Figure 19. *Benthic Index of Biotic Integrity (B-IBI) scores and biological condition categories for streams in the Puget Sound SERDP military base assessment project*

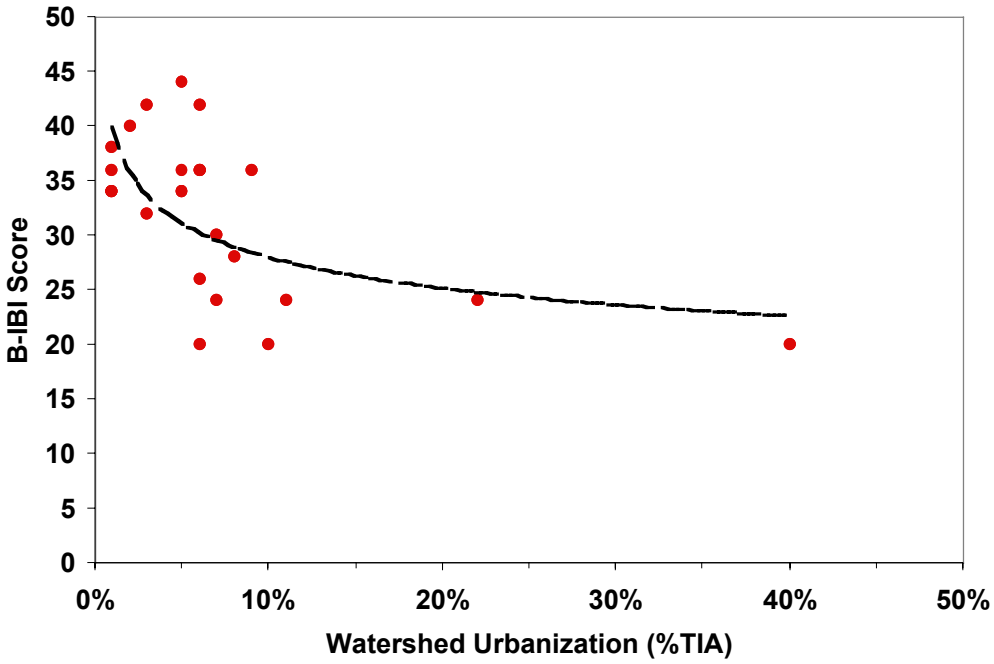

Figure 20. *Benthic Index of Biotic Integrity (B-IBI) scores in comparison to watershed total impervious area (%TIA) for Puget Sound SERDP military base streams*

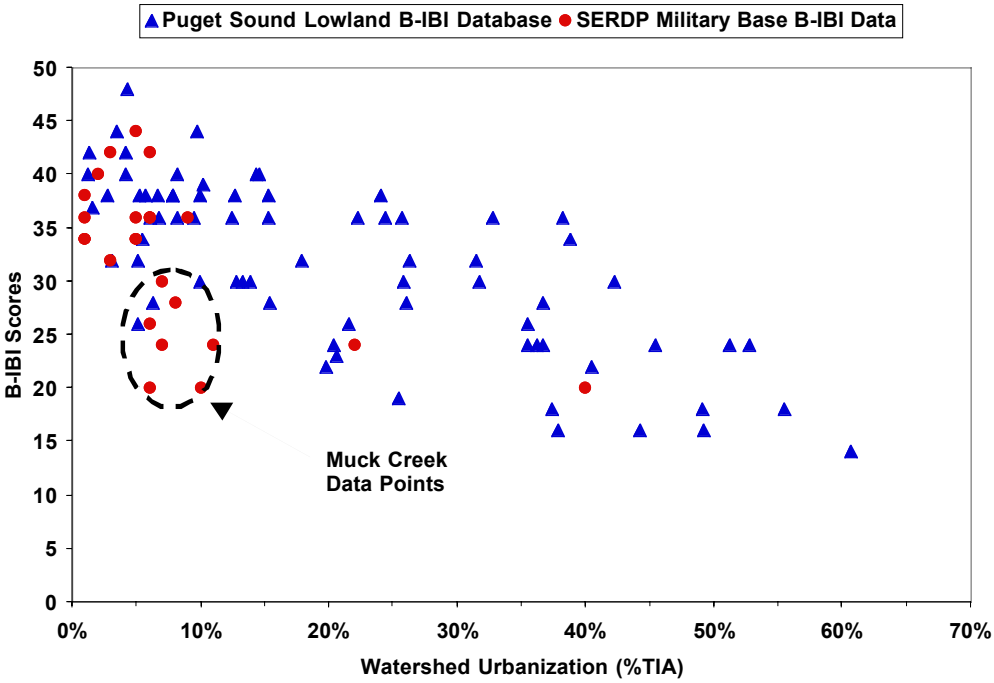

Figure 21. *Benthic Index of Biotic Integrity (B-IBI) scores in comparison to watershed total impervious area (%TIA) for Puget Sound SERDP military base streams and other (1997-2000) Puget Sound lowland streams*

Instream Habitat Analysis

After summarizing the instream habitat data for each stream segment the values were compared to those representing natural, reference conditions and values that were determined (based on best available science) to be indicative of properly functioning conditions (PFC). Based on this analysis, a habitat quality index (HQI) was developed in an effort to integrate several key quantitative parameters to describe overall stream habitat quality using a single score.

Matrix of Pathways and Indicators

In an effort to identify parameters indicative of ecosystem processes functioning in a manner that will maintain stable and healthy streams (for anadromous salmonid populations), *NMFS* (1996) developed the "Matrix of Pathways and Indicators" (MPI) as an evaluation tool to describe PFC. This matrix presents a number of environmental parameters important to production and survival of anadromous fishes and sets three condition levels for each parameter: (1) properly functioning, (2) at risk, and (3) not properly functioning. This matrix was also adopted by the Washington Conservation Commission (WCC) as a tool for evaluating stream conditions within the PSL eco-region.

Properly Functioning Conditions

Three main instream habitat parameters were used to develop the HQI: riffles, pools, and LWD. The means and variances for each parameter were calculated for each segment and compared to PFC values representing natural, reference conditions. The methodology for evaluating these parameters is outlined below, as is the scoring criteria used in the HQI process.

Riffle Habitat

Riffle habitat in each stream segment was quantified by calculating the surface area of wetted stream channel classified as riffles. The percentage total stream habitat classified as riffle habitat was also calculated. Generally, an equal proportion of pool and riffle habitat is considered optimum, thus the riffle fraction should be 40 to 60 percent (*Peterson et al*. 1992).

Pool Habitat

Pool habitat in each stream was quantified by calculating the surface area of wetted stream channel classified as pools. The percentage of total stream habitat classified as pool habitat was also calculated. Target conditions for pool frequency have been established by a number of authors. *Peterson et al.* (1992) suggest that pools should comprise 50 percent by area in streams with a less than 3% gradient. Greater than 55 percent by surface area has also been recommended for streams with a 0–2% gradient (*Peterson et al*. 1992). The NMFS MPI suggests that 30 pools/km for streams 6 m wide and 35 pools/km for streams 7.6 m wide indicate PFC.

LWD Frequency and Size

LWD frequency was compared to published frequency ranges in natural forested systems of the PNW. The low end of the natural range in several studies was 150 pieces/km [a range of 150–460 in *Murphy* (1989), a range of 150–400 in *Ralph et al*. (1994), and

140–670 for streams of similar size and gradient in *Beechie and Sibley* (1997)]. Especially large pieces of LWD initiate the formation of stable woody debris jams (*Naiman et al*., 2000). The Matrix of Pathways and Indicators suggests 50 pieces/ km that are at least 60 cm wide by 15 m long indicate PFC. Although NMFS did not categorize this size class as key pieces, the large size range is comparable to the Washington State Forest Practices Board's *Watershed Analysis Manual* (1997) and WDFW's *Wild Salmonid Policy* (1997) key piece size standard of 0.55-m diameter and 10 m in length for streams with a 6–10-m bankfull width. TFW key piece criteria is based on a volume calculation that allows variable diameters and lengths (*Schuett-Hames et al*., 1999a). The frequency of all wood that met minimum diameter criteria of at least 50 cm was calculated, and no minimum length requirement was used for comparison with the NMFS frequency standards (*NMFS*, 1996). Pool forming LWD and the zone LWD occupied within the channel were also collected, but not included in this report. The species composition of the LWD was included only in the wood quality index (WQI) metric within the habitat quality index (HQI) described below.

Habitat Quality Index

A multi-metric index, the habitat quality index (HQI), was developed during this study to assess the overall condition of the habitat in each stream segment. The HQI incorporates eight metrics important to salmonid production in third order streams to score an assessment segment with a single number representing the overall habitat quality of that reach (*Peterson et al*., 1992; *NMFS*, 1996; *May et al*., 1997; *Barbour et al*., 1999). Each of the individual metric scores was calculated from quantitative assessment data. The metrics in our index include (Tables 17 and 18):

- Pool frequency (# pools/ km stream)
- Percent pool habitat (based on surface area)
- Weighted pool quality index (PQI, modified from *Platts et al*., 1983)
- Percent riffle habitat (based on surface area)
- Weighted riffle quality index (incorporating embeddedness, cover, and substrate size)
- LWD frequency (# pieces/ km stream)
- LWD volume (m^3 / km stream)
- LWD quality index (incorporates % of coniferous pieces and key pieces with diameters greater than 0.5 m)

In order to develop a scoring scale that represents the possible range of metric values in the Puget Sound region, instream habitat data from 74 PSL streams that represented streams with a range of urbanization impacts (*May et al*., 1997) was reviewed. These data were collected using protocols comparable to the methods used by this study and is a large data set for similar individual metrics. The data distribution for each metric was determined by examining the quartile distribution of the PSL data set. Using this distribution and comparing the ranges of values for each metric to published values for natural conditions for similar sites, and the NMFS PFC-MPI (*NMFS*, 1996), the upper

and lower quartiles of the values for each metric were identified to describe high and low quality conditions, respectively.

The possible range of scores (either 1-3-5 or 1-4-7 for low, medium, and high values) for each metric was assigned based upon ecological function and our confidence in the quality of the data. The low, medium, and high categories correspond with the NMFS PFC table when possible (i.e., not properly functioning, at risk, and properly functioning). The higher possible maximum score (7) was assigned to pool, riffle, and LWD measures because these metrics were more quantitative, and more confidence was held in these data because they could be compared to data from natural, reference conditions. The lower metric score ranges were used for the three quality indices. A score was applied to each metric based upon quartile values of the best available PSL stream data. Those values for each metric falling into the lowest or highest quartiles were given low and high scores, respectively, and the middle 50 percent of the values were given the medium score. In defining our best conditions we acknowledge that all of the PSL watersheds likely have been influenced by the legacy of logging, agriculture, and stream cleaning, and that adequate reference values are difficult, if not impossible to determine (Tables 26 and 27).

Using techniques similar to the B-IBI, metric scores were then summed to determine an overall HQI score for each segment. Possible scores range from 8 (lowest quality) to 50 (highest quality). Ratings categories of low, medium, and high were again determined from the quartile distribution of HQI scores calculated from the PSL 74-stream data set. Since many of the segments fell into the medium-quality habitat category, medium-high and medium-low categories were defined using the middle two quartiles of the reference stream HQI scores to give the results better resolution. Assessed segments with summed HQI scores ranging from 8 to 23 were rated low-quality habitat, 24 to 31 were rated medium-low, 32 to 36 were rated medium-high, and segments with scores from 37 to 50 were rated high-quality habitat (Tables 17 and 18).

It should be noted that this HQI rating system is newly developed and should be tested in other streams before being accepted for general use. It is desirable from a watershed management perspective to have a simple, standardized method of rating and ranking stream segments.

Table 17. *Habitat Quality Index (HQI) metrics*

Parameter	Reference Site		HQI Range			HQI Code		
	Low Range	High Range	Low	Medium	High	Low	Medium	High
Pool frequency (# pools/km)	7-22	55-148	<23	22-55	>54	1	4	7
Percent of reach made up of pools (%)	1-11	34-56	<12	12-39	>39	1	4	7
Weighted PQI (frequency X score)	7-30	150-592	<31	31-149	>149	1	3	5
Percent of reach made up of riffles (%)	13-39	63-99	<40	40-44	>44	1	4	7
Weighted RQI (% area X score)	78-338	1563-7160	<339	339-1562	>1563	1	3	5
LWD frequency (# LWD/km)	7-50	166-360	<51	51-166	>166	1	4	7
LWD Volume (m^3/km)	0-38	267-956	<39	39-267	>267	1	4	7
Wood Quality Index (% coniferous + % >= 0.5 diameter)	0-50	115-180	<51	51-115	>114	1	3	5
Maximum Score								**50**

Table 18. *Habitat Quality Index (HQI) metrics*

Parameter	Reference Site Quartiles				HQI Code		
	Low	Med. Low	Med. High	High	Low	Med.	High
Pool frequency (# pools/km)	7-22	23-40	41-54	55-148	1	4	7
Percent of reach made up of pools (%)	1-11	12-22	23-33	34-56	1	4	7
Weighted PQI (frequency X score)	7-30	31-80	81-149	150-592	1	3	5
Percent of reach made up of riffles (%)	13-39	40-49	50-62	63-99	1	4	7
Weighted RQI (% area X score)	78-338	339-632	633-1562	1563-7160	1	3	5
LWD frequency (# LWD/km)	7-50	51-110	111-165	166-360	1	4	7
LWD Volume (m^3/km)	0-38	39-134	135-267	268-956	1	4	7
Wood Quality Index (% coniferous + % >= 0.5 diameter)	0-50	51-77	77-114	115-180	1	3	5
Maximum Score							**50**

The results of the HQI scoring for the SERDP Puget Sound stream surveys are shown in Figure 22. In general, the habitat quality ratings for these streams reflected the condition of the watersheds in which they are located. As with other PSL streams, the habitat conditions ranged from poor to excellent, with most streams falling in the fair and good ranges. Details of individual stream segment scores are included in the report sections covering each DoD installation.

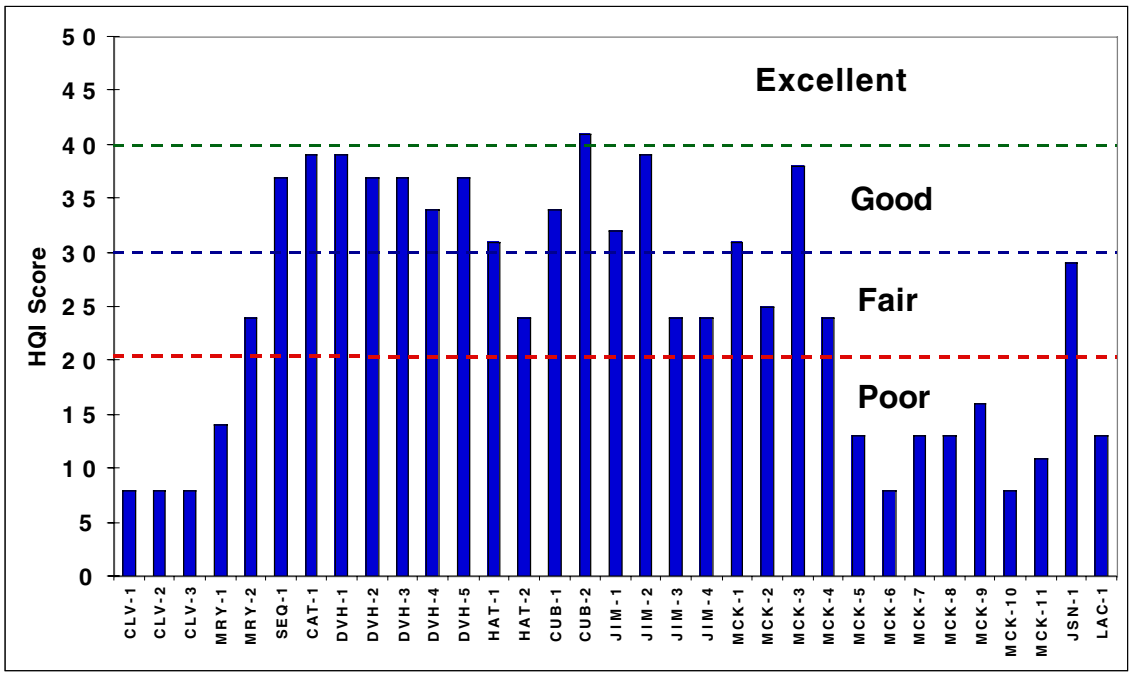

Figure 22. *Habitat Quality Index (HQI) scores for SERDP Puget Sound military base stream assessment surveys*

MILITARY INSTALLATION DATA SUMMARY
MCCHORD AFB: CLOVER CREEK

McChord Air Force Base (AFB) is located near Tacoma, Washington within the Water Resource Inventory Area 12 (WRIA-12). Figure 23 shows the location of WRIA 12 in the state of Washington. Figure 24 shows McChord and Fort Lewis and the main watersheds in each. Clover Creek enters McChord AFB on the eastern boundary of the base and flows east to west for less than 2 miles across the base. The North Fork of Clover Creek is the main tributary feeding the creek prior to it entering McChord AFB. The Upper Clover Creek watershed lies in SE Pierce County and is dominated by residential development. Most of the upper basin is in outwash soils, with good infiltration capacity, but a substantial portion is on till soils, which have a much higher run-off potential (*USGS*, 1996). Morey Creek, a tributary of Clover Creek also enters the base on the eastern boundary and joins Clover Creek just upstream of the main runway. Morey Creek originates from Spanaway Lake, located to the southeast of the base. Spanaway Lake is fed by Spanaway Creek, which originates in Spanaway Marsh, a relatively intact wetland system located on Fort Lewis Army Base. This lake is a shallow, spring-fed lake and often has problems with eutrophication (*USGS*, 1996). In addition, before Morey Creek merges with Clover Creek, a concrete dam forms a small fishing pond, making Morey Creek and Spanaway Creek inaccessible to native salmonids migrating upstream to spawn. Clover Creek was relocated and channelized in the late 1930's from its natural channel to accommodate the airfield. The creek runs underground in two corrugated steel pipes for one-half mile as it passes under the main runway. Clover Creek contains native cutthroat trout and also supports coho salmon (*Pierce County*, 1997). The creek flows into Steilacoom Lake in the city of Lakewood (Figure 25).

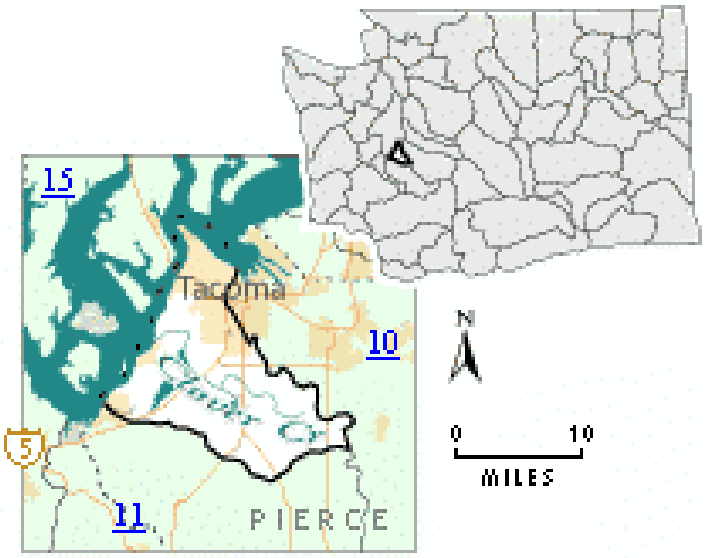

Figure 23. *Clover Creek watershed location*

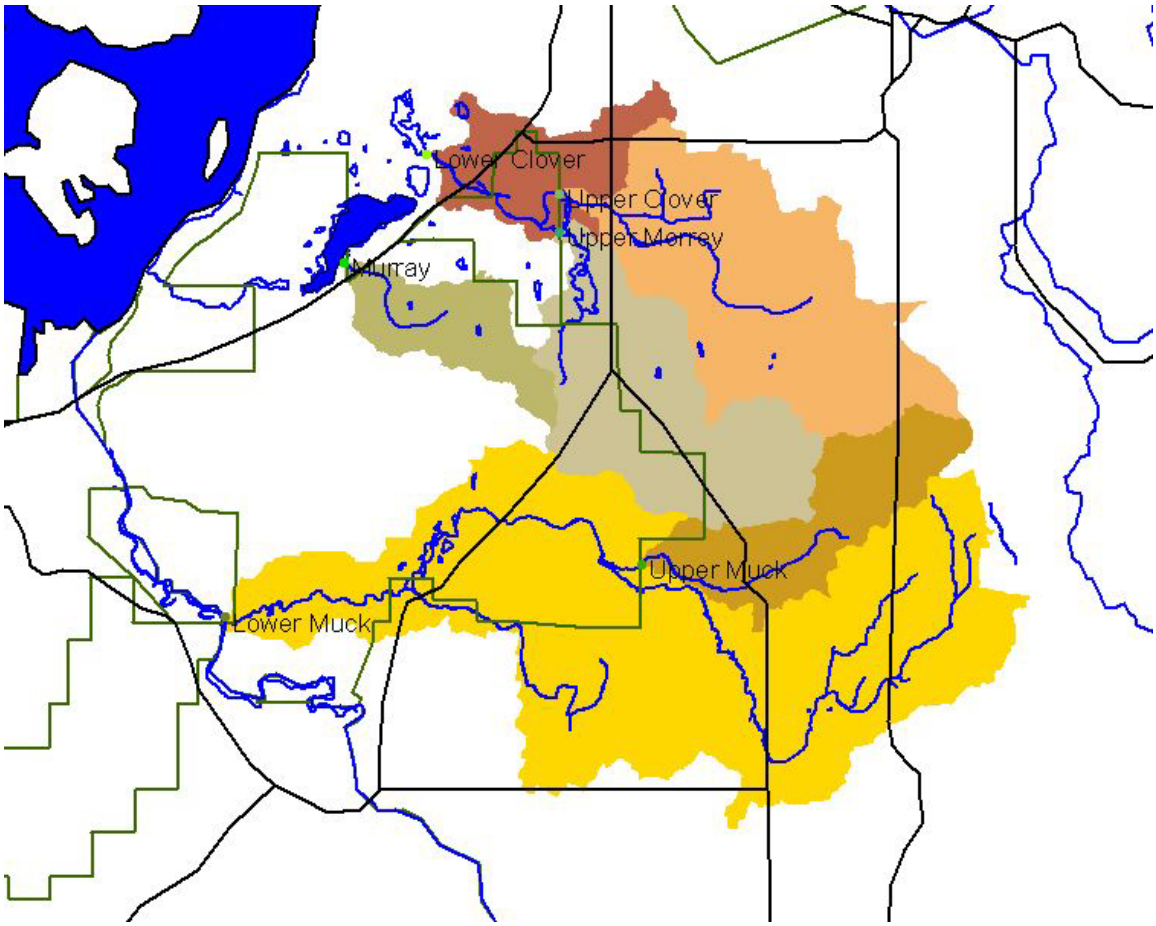

Figure 24. *McChord AFB and Fort Lewis watershed location*

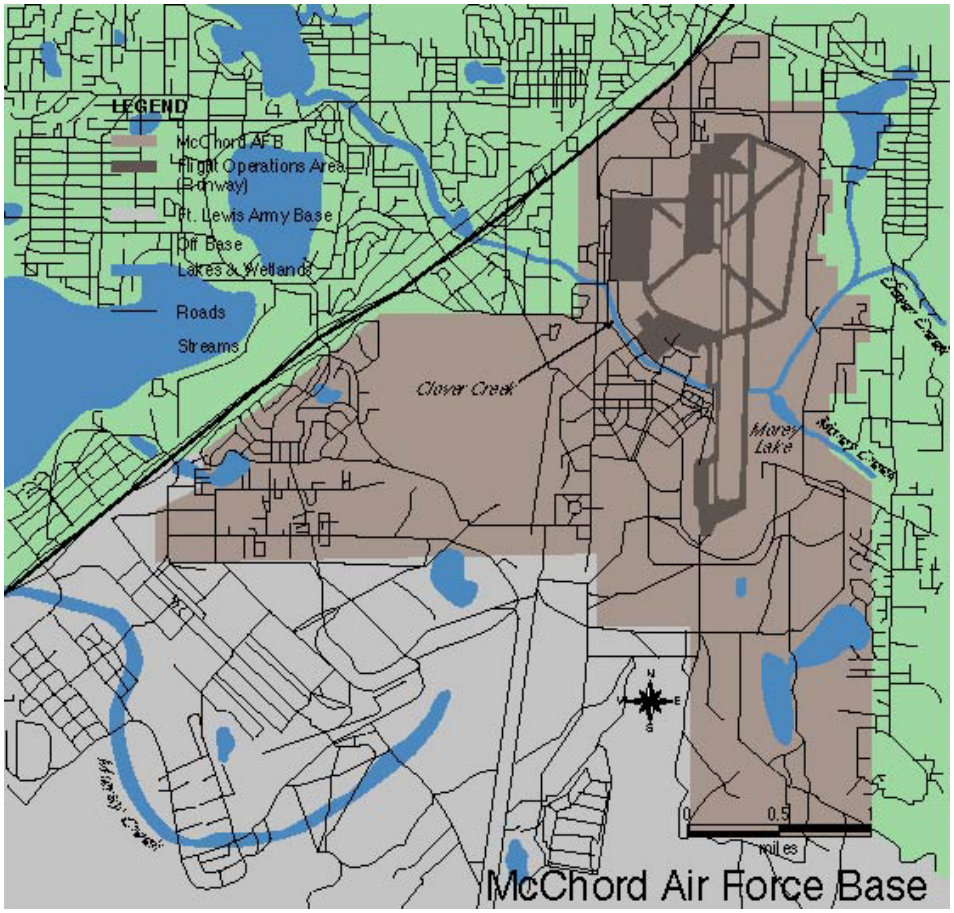

Figure 25. *Clover Creek and McChord Air Force Base*

The main command at McChord AFB is the 62nd Airlift Wing. In addition, the 446th Airlift Reserve is stationed at McChord AFB. Their primary mission is to deploy and transport military personnel, equipment, and logistical material using military transport aircraft. The 62nd Airlift Wing is composed of the 4th, 7th, and 8th Airlift Squadrons and the 62nd Operations Support Squadron, which includes the Environmental Support Detachment, which was the primary point of contact for this project.

Clover Creek receives stormwater run-off from the base, especially the large impervious areas of runway, hangers, and flightline. Storm water discharges are regulated under the nation-wide US-EPA General Storm Water Permit and are specified in federal regulations by a National Pollutant Discharge Elimination System (NPDES) permit. An important item of the permit is preparation of a Stormwater Pollution Prevention Plan (SWPPP). The plan for McChord AFB requires only visual inspections of the outfalls received by Clover Creek on a quarterly basis (*McChord SWPPP*, 1999). There are thrity-three stormwater outfalls that discharge directly into Clover Creek from McChord AFB (*McChord SWPPP*, 1999). During a visual inspection, the observer looks to see if there is an oily sheen visible or any other change in the nature of the water. Testing for traces of chemical pollutants is done on only four separately permitted outfalls that drain the main runway area. As part of the SWPPP, every major outfall to Clover Creek runs

through an oil/water separator (OWS). There are a total of 62 OWS on McChord AFB (*McChord SWPPP*, 1999). Most of these OWS are older dual-chamber devices or coalescing plate separators. These devices have been shown to have a very limited capability of treating low concentrations of oil, but are effective at trapping relatively small quantities of high concentrations of oil such as would be found after an oil spill on the runway or flight line. OWS are generally not considered state-of-the-art stormwater treatment BMPs. The stream receives no industrial discharges. Any water that may pose a risk is plumbed to the sanitary sewer system and treated prior to discharge. The creek is also sampled periodically at the western (downstream) base boundary.

There have been several fuel spills documented at McChord AFB over the course of its history. Most of these spills have been on the flightline area and most have been the result of aircraft fueling or maintenance operations (*McChord SWPPP*, 1999). In general, good housekeeping practices are effective at minimizing spill potential. Most aircraft maintenance is conducted inside the hangers and is not exposed to stormwater run-off. Aircraft fueling operations are conducted on the flightline and have the most potential for a mishap, although personnel training and safety systems make this risk minimal.

Portions of both McChord AFB and Fort Lewis Army Base are within the SPSP ecosystem. This is a unique ecosystem that once covered much of the southern Puget Sound, from what is now Tacoma to south of present-day Olympia. This is currently a highly fragmented and degraded ecosystem over much of its historic range. The SPSP was a patchwork of grasslands, wetlands, oak woodlands, pine savannas, and open forests on the gravelly, outwash plains of the southern lowlands of Puget Sound (*Kruckeburg*, 1991). These prairies are flat or mounded, covered with a dense cover of grasses, moss, and lichens, and bordered by trees. Fort Lewis and McChord currently encompass the largest remaining prairies in South Puget Sound. This habitat is unique, when contrasted with the thick forests of Western Washington, because of its well-drained soils, dense grasses, groves of Oregon white oak, and patches of lodge-pole, and ponderosa pine. Historically, native peoples used fires to maintain these open areas for hunting and gathering (*Kruckeburg*, 1991). Development, agriculture, weedy species, and military training activities threaten the existence of this habitat and its rare animal species like the western gray squirrel and bluebird. See Appendix D for more about the SPSP ecosystem. *Dunn and Ewing* (1997) is the best source of scientific information on this unique Puget Sound landscape.

Clover Creek Data Analysis

Watershed Characterization

The percentage of the Clover Creek watershed that remains as native forest or prairie (grassland) is generally below 30% for most sub-basins (see Table 29). In most cases, very little of the forested area is dominated by the mature coniferous species that are native to the region. In addition, very little of the native SPSP ecosystem is left intact, although a large percentage of the total SPSP in the Clover Creek watershed is located on McChord AFB. Landscaped areas, herbaceous vegetation (lawns, golf courses, etc.), shrubs, and various exotics characterize the majority of vegetated areas within the watershed. There is also minimal natural riparian forest within the riparian corridor of

most of the stream channels within the watershed. Areas where natural forest cover remain are typically dominated by deciduous species including red alder, willow, and big-leaf maple. Mature, coniferous-dominated riparian corridors still occur in isolated areas in these urbanizing sub-watersheds.

The sub-basins of Clover Creek are generally dominated by medium to high-density residential development and commercial areas, especially along the major road corridors (*Pierce County*, 1997). The lower sub-basins are generally more developed than the upper watershed (see Table 19). McChord lies within the lower Clover Creek sub-basin, which has a total impervious area (% TIA) of 60%. This level of imperviousness is typical of "urban" watersheds in the PSL region (*May et al*., 1997). The bulk of the contributing impervious surface area located on McChord AFB is in the form of runway, flightlines, and buildings/hangers. This is a significant portion of the total imperviousness on the base and most of it is directly connected to the creek via the stormwater conveyance network (*McChord SWPPP*, 1999). The remainder of the base is very similar to the surrounding community, with roads, residential and office developments, as well as commercial areas and other structures. A large portion of the base, to the south of the runway, is natural area.

Table 19. *Land-cover and land-use in the Clover Creek watershed*

Sub-Watershed	**Total Impervious**	**Native Forest**	**Native Grass**	**Bare Soil**	**Urban Forest**	**Urban Grass**	**Urban Paved**
Lower Clover Creek	**60**	4.5	16.6	2.2	13.1	35.7	27.8
Upper Clover Creek	**42**	15.5	19.2	1.9	25.3	30.3	7.7
Morey Creek	**38**	17.6	12.4	0.7	41.5	21.3	5.1

Basin Land-use

- Table 19 summarizes the land-cover and land-use data for the watershed. McChord AFB itself is approximately 44% impervious, including the runway and flightlines.
- Road density in the McChord AFB sub-basin is 8.76 km/km^2 in the area contributing to Clover Creek. Generally, a road density over 3 km/km^2 is considered high.
- Grass/lawn and landscaped areas dominate the developed portions of the base.
- Relatively large areas of native prairie, wetland, and forest still exist on the base. These areas contain remnants of native flora and fauna, including several endangered species. DoD and The Nature Conservancy of Washington are jointly managing these areas.

Riparian Corridor Continuity

- Total number of stream crossings on the segment of Clover Creek that flows through McChord AFB is 6 crossings per km of stream, which is considered high and is indicative of the highly fragmented nature of the stream-riparian corridor.
- The runway is the largest single stream crossing, with a culvert approximately 1 km in length. This culvert, although quite long, is passable by both adult and juvenile salmonids.

Riparian Integrity

- The riparian zone of clover Creek on McChord AFB is nearly non-existent. Where there is riparian vegetation, it is dominated by lawn, woody shrubs, herbaceous plants, and exotic species (see Appendix F—data maps).
- The creek is located within a deep, channelized "ditch" that is encroached upon on both sides by flightline area, parking lots, buildings, and other developed areas. The mean buffer with is less than 5 m (see Appendix F—data maps).
- Only small patches of riparian forest remain along the creek on base.
- Landscaping often includes exotic/invasive species such as Himalayan blackberry (*Rubus discolor*), Reed Canary grass (*Phalaris arundinacae*), and Japanese knotweed (*Polygonum cuspidatum*).

Canopy Cover

- All Clover Creek reaches on McChord AFB have less than 20% canopy cover (see Appendix F—data maps).
- High temperature and low dissolved oxygen (DO) have been identified as water quality problems in Clover Creek where it leaves McChord AFB (*USGS*, 1996).

Large Woody Debris

No segments of Clover Creek on McChord AFB contained LWD within the PFC range identified in the current scientific literature. In fact, there was no LWD found in the entire length of the creek within the base. In addition, LWD recruitment potential within these segments was essentially non-existent (see Appendix F—data maps).

Channel Morphology

- With the exception of the upstream segment of the creek, all segments surveyed within the base had unstable or armored (rip-rap) streambanks, suggesting that conditions are not properly functioning within the channel with respect to hydrology and channel form (see Appendix F—data maps).
- Channel complexity was also quite low. The stream is essentially one long glide with no sinuosity within the base. In addition to the lack of meanders, the channel has been dredged into a deep ditch for almost its entire length on

base, with no natural floodplain area or off-channel wetlands present. Glides are intermediate habitat units that have characteristics of both pools and riffles but provide little of the functional capabilities of either. Although relatively deep and slow during baseflow conditions like pools, glides provide little refuge during peak flows. Glides are also usually slow water habitat where finer sediment predominate, making them poor spawning habitat. There was a general shift in habitat dominance from balanced pool-riffle morphology to a glide-dominant habitat structure in Clover Creek. This is typical of urban streams in the PSL (*May et al*., 1997).

Spawning Habitat

- There is no usable spawning habitat (riffles) in the survey reaches of Clover Creek on McChord AFB (see Appendix F—data maps).
- Riffle quality index (RQI) scores indicate the quality of spawning habitat in each riffle. High quality riffles have clean substrate, low embeddedness, and abundant cover. Mean RQI scores on the Clover Creek segments were poor.

Rearing Habitat

- There is no usable rearing habitat (pools) in the survey reaches of Clover Creek on McChord AFB (see Appendix F—data maps).
- Pool quality index (PQI) scores indicate the quality of rearing habitat in each pool. High quality pools are generally deep, large in size, and have abundant cover. Mean PQI scores on the Clover Creek segments are poor. The NMFS MPI suggests 30 pools/km indicate PFC.

Habitat Quality Index (HQI)

- The habitat quality of the assessed segments of Clover Creek on McChord AFB (see Appendix F—data maps) was evaluated using the HQI. The summed score of eight metrics determined the final HQI score (see results section for details). The Clover Creek HQI scores were all in the low habitat quality category (mean score = 8 out of a possible 50).

Biological Integrity

- Clover Creek on McChord AFB had a B-IBI score of 20 (out of a possible 50) and is rated as poor (see Appendix F—data maps).
- No salmonids were noted in Clover Creek on McChord AFB during project field surveys.

Chemical Water Quality

- This study did not specifically assess chemical water quality.
- See University of Washington water quality assessment report (see Appendix E).

Clover Creek MCChord AFB photographs

Clover Creek riparian zone upstream of runway culvert

Clover Creek upstream of McChord AFB runway

Clover Creek runway culvert upstream of McChord AFB runway

McChord AFB runway

Clover Creek runway culvert downstream of McChord AFB runway

Clover Creek road crossing on McChord AFB

Clover Creek riparian downstream of McChord AFB runway

Clover Creek on McChord AFB near flightline

Clover Creek Channel on McChord AFB

Clover Creek Channel on McChord AFB

Clover Creek at McChord AFB downstream boundary

Recommendations

1. Salmonid habitat in Clover Creek is generally degraded throughout the watershed due to the cumulative impacts of human land-use activities (*Pierce County*, 1999). This is also true of the segments of the creek flowing through McChord AFB. The creek is channelized and has little of its natural habitat complexity and diversity. There is limited opportunity to improve instream habitat conditions within the McChord segments, but there are a few options, including:
   - Holding pool creation
   - LWD enhancement
   - Spawning gravel addition
   - Streambank revegetation
2. The riparian corridor of Clover Creek on McChord AFB can be significantly improved by removal of exotic vegetation, lawn, and landscaped areas. These areas should be revegetated with native trees, shrubs, and groundcover. The buffer width in each segment of the stream should be maximized, with consideration given to the relocation of parking lots or other non-essential infrastructure. The goal should be to increase canopy cover and improve LWD recruitment potential over the long term.

3. The runway culvert is problematic. Short of routing the creek to the south of the runway, there is little that can be done to improve conditions within the culverted section of the creek. Base personnel should accomplish inspection and removal of debris-jams routinely so as to prevent any migration barriers from forming.
4. Water quality should be a significant cause for concern on McChord AFB. With the close proximity of aviation fueling operations and other potentially hazardous activities so close to Clover Creek, pollution prevention must be the highest possible. The use of stormwater BMPs for all impervious surfaces is strongly advised.
5. The main function of concern in the McChord section of Clover Creek is to provide unrestricted upstream passage for adult salmonids and downstream passage of juvenile salmonids. Maintaining this function should be a primary goal of aquatic resource management for Clover Creek on base.

MILITARY INSTALLATION DATA SUMMARY
FORT LEWIS: MUCK, MURRAY, AND SEQUALITCHEW CREEKS

Fort Lewis Army Base is located south of Tacoma, Washington within the Nisqually River basin. Figure 26 shows the main sub-basins located within the jurisdiction of Fort Lewis. These include Muck Creek, Murray Creek, and Sequalitchew Creek. Figure 27 shows the boundaries of the Fort Lewis Army Base along with the main watersheds. Fort Lewis is located just south of McChord AFB, with both installations sharing portions of the Clover and Murray creek sub-basins.

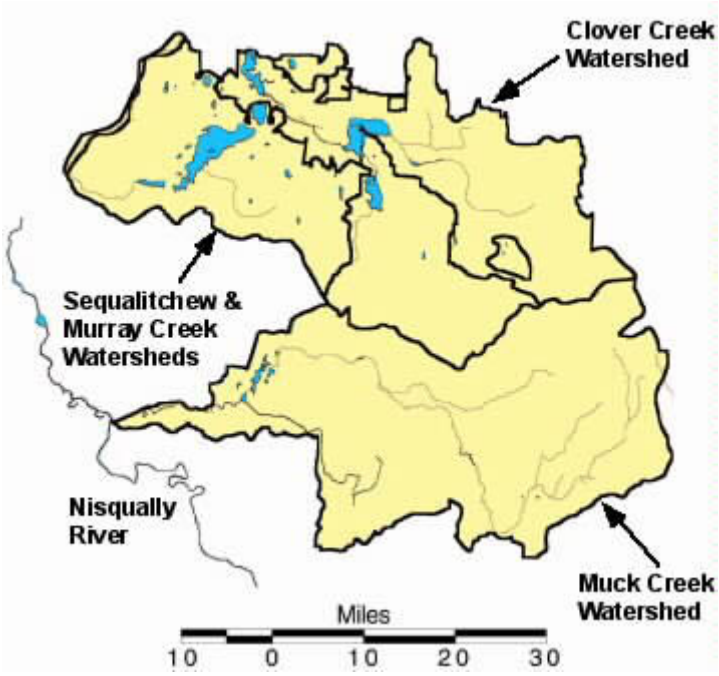

Figure 26. *Fort Lewis and Fort Lewis watershed locations*

The main command at Fort Lewis is I Corps. The primary mission of I Corps and other active and reserve U.S. Army units attached to the base is to conduct training activities to sustain and enhance the unit readiness for both wartime and peacetime military operations. Training operations include infantry maneuvers, military vehicle operations using tanks, armored personnel carriers, and other tracked or wheeled vehicles, and live-fire operations on one of several ranges and "impact areas" located within the Fort Lewis base boundaries. In addition, there are combat aviation operations that are part of the training activities at Fort Lewis. Both fixed-wing and helicopter assets are utilized for these operations. Live-fire gunnery operations include small arms and heavy artillery exercises. Training and unit readiness are the top priorities of the U.S. Army at Fort Lewis.

Fort Lewis encompasses over 86,000 acres, which is divided into three main areas of land-use: the developed cantonment area (~7,500 acres), training areas (~75,500 acres),

and the Gray Army Airfield (~3,000 acres). The cantonment area contains military offices, the hospital complex (Madigan), residential housing, parks, recreational facilities, military dormitory housing, commercial areas, industrial facilities (primarily vehicle maintenance), and logistical support facilities. The cantonment area is very similar to the local civilian communities that surround the base, both in land-use categories and level of development.

The training areas of Fort Lewis contain the majority of the undeveloped, natural areas within the base jurisdiction. Training areas include over 52,000 acres of native coniferous forest, 4,500 acres of wetlands, as well as nearly 21,000 acres of prairie and oak savanna. Most of the ground operations and tracked vehicle maneuver training occurs within these training areas. Fort Lewis also includes two live-fire "impact areas" (Figure 27) where artillery, tank, mortar, and other munitions are utilized for combat training. All of these training activities are closely controlled and are designed to minimize the impact on native ecosystems. Established in 1991, the Army's Integrated Training Area Management (ITAM) Program incorporates a connection between training and land conservation and reminds us that land management should not only provide for environmental and natural resource protection, it should also support the training mission. ITAM consists of four divisions: Land Condition Trend Analysis (LCTA), Land Rehabilitation and Maintenance (LRAM), Environmental Awareness (EA), and Training Requirements Integration (TRI). TRI oversees all training activities on base. LCTA conducts studies and monitors environmental impacts. LRAM is responsible for removing Douglas fir and Scotch broom (generally with mechanical methods) within the prairie ecosystem areas of the base. LRAM has also installed "siber stakes," which designate off-limit areas for tracked vehicles. In addition, they have constructed creek crossings, which are posted as authorized ford crossings. EA is responsible for education of on-base civilians and military personnel.

The Fort Lewis Fish and Wildlife Management Plan directs natural resource conservation efforts on base. The Fish and Wildlife Program has planted Oregon white oak and Ponderosa pine seedlings, as well as cottonwood, willow and Oregon ash within the Muck Creek riparian corridor. Under the Fort Lewis Regulations (FL 200-1), vehicles are not allowed "off-road" within 50 m of any body of water. Extensive wetland rehabilitation projects have been undertaken throughout the Muck Creek watershed within Fort Lewis. This work has included restoration of historic, natural water levels, as well as habitat enhancement work. In addition, Fort Lewis has a comprehensive fire management program in order to maintain open training areas and reduce fuel for accidental fires, as well as to help maintain the unique SPSP ecosystem areas of the base.

Since the early 1980s Fort Lewis has been involved in extensive efforts to re-vegetate riparian zones of the major streams within the installation. Several miles of stream banks have been planted through in-house personnel, contracts, volunteer efforts, and cooperative efforts with the Nisqually Tribe and The Nature Conservancy of Washington. Beyond the standard reasons for establishing a contiguous and biologically functional riparian ecosystem, this effort is regarded as a long-term solution to exotic vegetation (mostly reed canary grass) control within the stream corridors on Fort Lewis. Reed canary grass control is considered a major management priority for both streams and wetlands on the base. As such, much effort and expense has been, and continues to be,

directed at controlling this invasive species. Until native riparian plants become large enough to shade out canary grass, two primary methods are utilized on Fort Lewis to help reduce the overall population of this species. In areas where encroachment into the stream channel is extensive, resulting in blockages to flow and fish migration, vegetative mass and associated roots are removed mechanically. Upland sites and other areas of infestation not directly connected to stream channels are treated with herbicides as needed to maintain control and prevent spreading.

Several sections of Muck Creek have been identified as deficient in LWD. Fort Lewis has undertaken projects in the past to supplement existing, natural LWD within various stream segments located on the installation. This has included anchoring logs and root wads, as well as installation of log weirs in several streams, including Muck Creek. Increasing available spawning habitat has also been identified by Fort Lewis resource managers as a viable method to increase populations of various salmon and trout species. This has been accomplished at several streams on the installation by removal of silt in selected locations, and placement of appropriately sized gravel within the stream channel. This not only increases the amount of spawning habitat available, but also provides a higher quality substrate that is composed of gravel mixes ideal for targeted species for spawning, all of which increases survival rates of native salmonids.

Portions of Fort Lewis Army Base are within the South Puget Sound Prairie (SPSP) Ecosystem. This is a unique ecosystem that once covered much of the southern Puget Sound, from what is now Tacoma to south of present-day Olympia. This is currently a highly fragmented and degraded ecosystem over much of it's historic range. The prairies of South Puget Sound were a "patchwork" of grasslands, wetlands, oak woodlands, pine savannas, and open forests found on the gravelly, outwash plains of the southern lowlands of Puget Sound (*Kruckeburg*, 1991). These prairies are flat or mounded, covered with a dense cover of grasses, moss, and lichens, and bordered by trees. Fort Lewis currently encompasses the largest remaining prairie ecosystem in South Puget Sound. This habitat is unique, when contrasted with the thick forests of Western Washington, because of its well-drained soils, dense grasses, groves of Oregon white oak, and patches of lodge-pole, and ponderosa pine. Historically, native peoples used fires to maintain these open areas for hunting and gathering (*Kruckeburg*, 1991). Development, agriculture, weedy species, and military training activities threaten the existence of this habitat and its rare animal species like the western gray squirrel and bluebird. See Appendix D for more about the SPSP ecosystem. *Dunn and Ewing* (1997) is the best source of scientific information on this unique Puget Sound landscape.

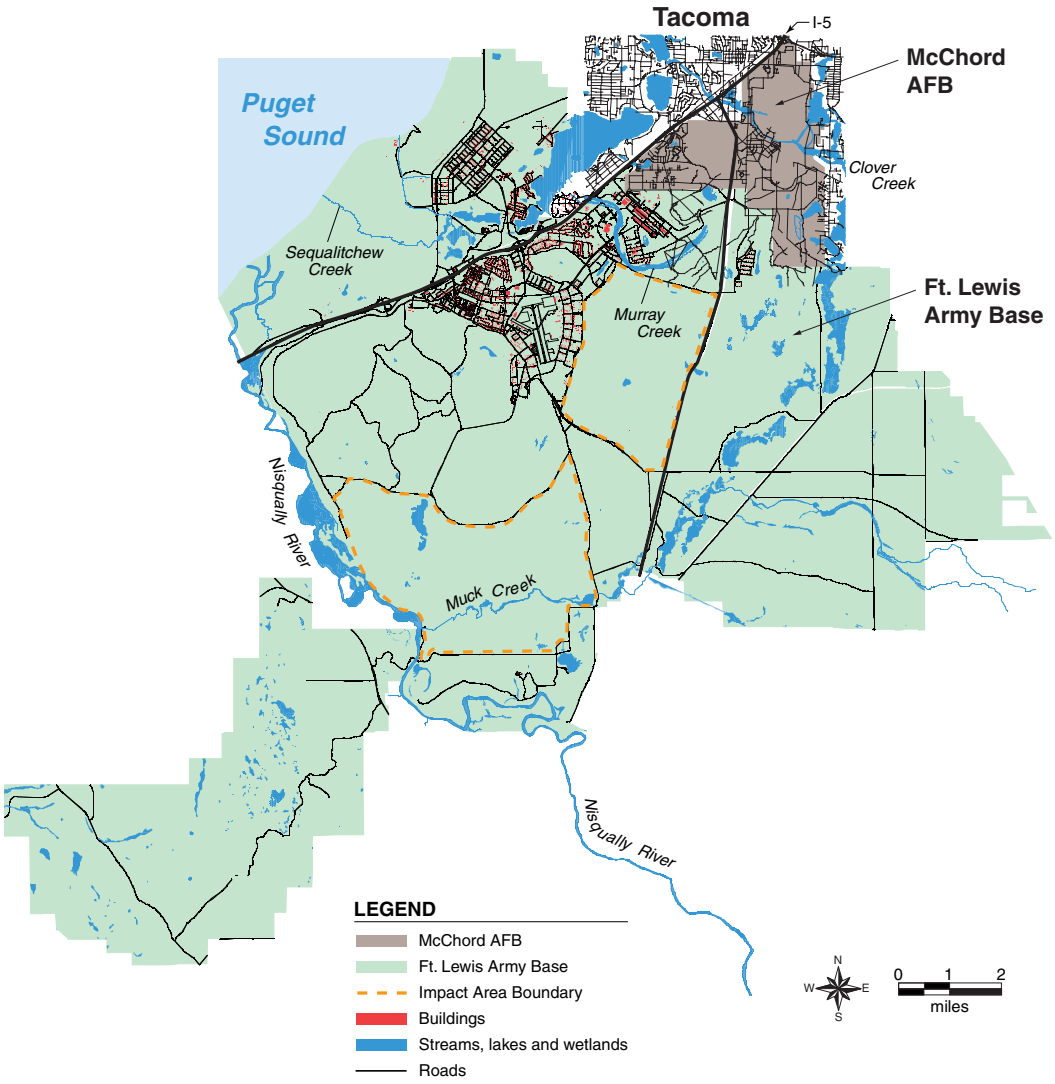

Figure 27. *Fort Lewis Army Base and the watersheds within its jurisdiction*

Table 20. *Land-use and land-cover data for Fort Lewis watersheds (%)*

Watershed	Total Impervious	Native Forest	Native Grass	Bare Soil	Urban Forest	Urban Grass	Urban Paved
FORT LEWIS							
Lower Muck Creek	**20**	38.5	26.8	0.1	23.2	8.1	3.3
Upper Muck Creek	**29**	31.4	21.4	0.6	24.3	15.9	6.5
Muck Creek Total (Including Lacamas and Johnson)	**19**	35.0	25.0	0.5	24.5	11.0	4.0
Murray Creek	**36**	20.3	11.0	1.1	47.2	12.1	8.4
Lacamas Creek	**19**	44.5	22.0	0.5	22.5	8.0	2.5
Sequalitchew Creek	**36**	25.8	8.9	1.3	42.8	11.1	10.2

Muck Creek

The Muck Creek watershed is the largest sub-basin in the lower Nisqually River basin and the most important with respect to natural production of salmonids as well (Figure 28). The Muck Creek watershed is less than 20% impervious and has over 60% native vegetation cover (see Table 30). Muck Creek consists of several tributary streams, with Lacamas Creek and Johnson Creek being the most significant. The entire Muck Creek watershed encompasses approximately 92 square miles, with the lower 7 miles of creek within the Fort Lewis Army Base. Within Fort Lewis, the creek is relatively intact, with good riparian buffer zones, and fairly natural instream habitat. Outside the base, the watershed is mainly rural, with a mixture of residential and agricultural land-use. The town of Roy, WA is located near the center of the watershed, just outside Fort Lewis, near the confluence of Lacamas and Muck creeks. The level of suburban development along the SR-7 corridor and in the headwaters of Muck Creek is, however, increasing. Currently there are no chemical water quality problems noted for Muck Creek, although the potential for high summer temperatures and low dissolved oxygen (DO) levels is present. The creek does experience frequent intermittent flows and may dry up in sections during seasonal (late summer) low-flow periods. This is at least partially due to the permeability of the glacial outwash soils found in the middle and upper parts of the watershed, combined with the regional lack of precipitation in late summer. In general, the tributary streams (Lacamas and Johnson) do not experience these low flow problems due to their extensive headwater and off-channel wetlands. There are also extensive wetlands located in the headwaters and middle reaches of Muck Creek itself. These

wetlands (and lakes) typically provide year-round flow to downstream sections of the creek (Figure 28).

Muck Creek typically supports over 25% of the natural chum production in the lower Nisqually (WRIA-11) region. The creek also supports anadromous coho and steelhead, as well as resident cutthroat trout. The low-flow and semi-ephemeral nature of the creek presents some limitations to salmonid utilization in the early fall. Typically there is no chinook or pink salmon utilization of lower Muck Creek unless early fall rains provide enough flow to support spawning of these species. However, late fall and winter utilization by both chum and coho salmon is usually extensive. Resident cutthroat and rearing coho make extensive use of the wetlands located in the headwaters and middle segments of Muck Creek. These species also utilize Lacamas and Johnson creeks as well as their associated wetlands. Steelhead generally utilize the creek in winter and spring seasons, but are thought to migrate into the Nisqually early in the summer as flows begin to decrease. Historically, coho, chum, steelhead, and cutthroat have utilized Muck Creek from its mouth to the headwaters. Recently, low flow problems have been severe enough that salmonid utilization (except for resident cutthroat use) has been limited to the lower and middle segments of the creek, below Chambers Lake (Figure 28).

There are approximately 100 wetlands, covering almost 3,000 acres within the boundaries of Fort Lewis. In addition, about 500 acres of lakes exist on base. Of the natural wetlands on base, there are about 600 acres of emergent marsh, 1,000 acres of scrub-shrub marsh, and over 1,200 acres of forested wetland. The majority of these wetlands occur within the riparian corridors of the Nisqually River, Muck Creek, Johnson Creek, and Lacamas Creek. Prior to government acquisition of Fort Lewis in the early 1900s, many of the wetlands were ditched, drained, or filled as the prairie and forest areas were converted to agriculture. This is especially true of the upper reaches of Muck Creek, including the north and south headwater branches. This loss of historic wetlands likely has exacerbated the low flow problems that naturally occur in this prairie stream system. In addition several of the lakes and wetlands on base have outlet weirs to control water level and reduce flooding. These include Chambers Lake and Johnson Marsh in the Muck creek watershed. Both of these weirs are designed to allow salmonid migration. Most of the wetlands on base have been invaded by exotic vegetation (reed canary grass being the most troublesome) and the base has instituted an extensive vegetation removal program to counter this threat to native biodiversity.

Fort Lewis, like all DoD installations also has a Stormwater Pollution Prevention Plan (*Fort Lewis SWPPP*, 1998). The main cantonment area, North Fort Lewis (area of the base on the NW side of I-5), and northern area of the base that includes the main Logistics Center and Madigan Army Hospital are the most extensively developed sections of the base. Most of the impervious surface area lies within these drainage basins. Cantonment area run-off is routed to Puget Sound via an unlined drainage channel that runs under Sequalitchew Creek just downstream of the outlet of Sequalitchew Lake. Run-off from developed areas of North Fort Lewis drains into Sequalitchew Creek and the same drainage channel noted above. The Logistics Center and Madigan Hospital complex both drain into Murray Creek. All stormwater outfalls that drain vehicle maintenance areas or industrial areas are equipped with oil-water separators. In addition,

conventional stormwater detention ponds and vegetated swales are commonly used to treat stormwater run-off prior to discharge.

Based on information summarized in a recent WA-DOE report (*Sinclair*, 2001), intermittent streamflow conditions are likely a natural occurrence in the central watershed of Muck Creek. The hydro-geologic characteristics of the upper watershed are such that streamflow is often maintained from groundwater sources and from headwater wetlands, even during the summer baseflow period during most years. However, the hydro-geologic characteristics of the central basin (basically from the upstream Fort Lewis boundary to the Ellsworth Woods area) are such that surface flow is often lost to groundwater and hyporheic conditions tend to exist in the middle reaches of the creek during the dry summer period. The report indicates that groundwater movement is generally toward the west or northwest in the Muck Creek watershed from upland recharge areas in the eastern watershed toward the lower creek at the Nisqually River. For this reason, the lower creek generally also maintains perennial flow throughout the summer dry period from groundwater sources and wetlands located within the lower watershed. The report concludes that, although human activities have affected water storage and flow in the Muck creek basin (including the wetland areas of Fort Lewis in the central basin), these impacts have had a minimal affect on streamflow patterns in the creek. Seepage losses from the creek to groundwater have been, and continue to be, greatest in the central Muck Creek basin where the stream is perched above the groundwater table and where surface water is naturally lost as the stream traverses the highly permeable outwash soils located in that sub-basin area around the town of Roy, WA. Past human activities, such as stream channelization for farming, may have contributed to the surface water loss, but the magnitude of these alterations is difficult to quantify.

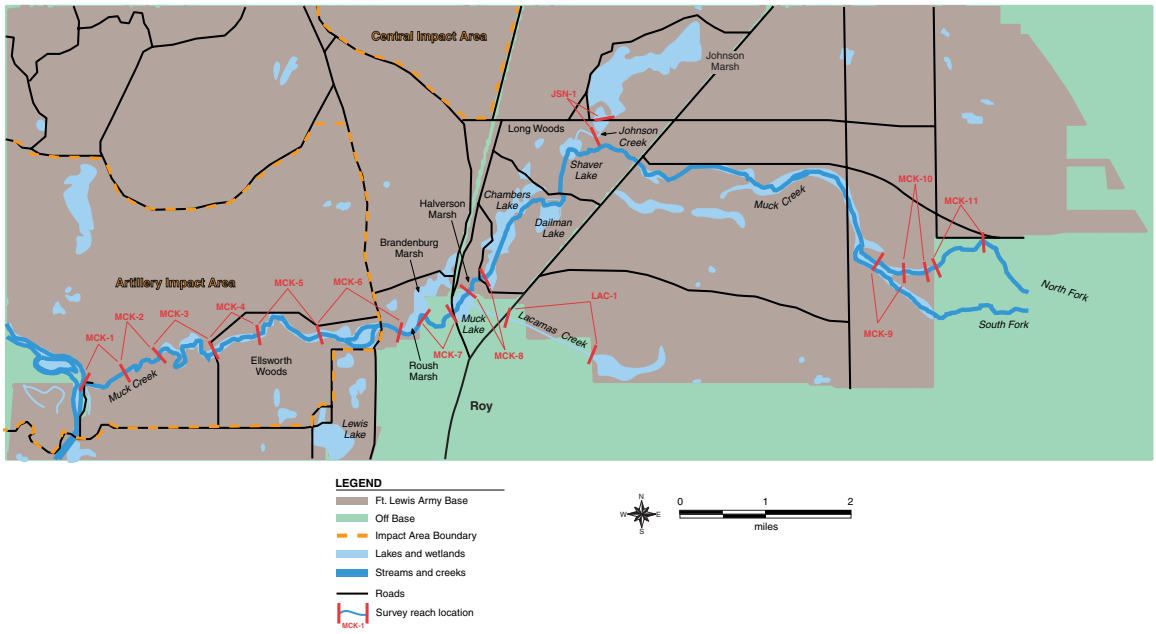

Figure 28. *Fort Lewis Army Base, showing the Muck Creek watershed, including the tributaries of Johnson and Lacamas creeks*

Muck Creek Data Analysis

Watershed Characterization

The percentage of the Muck Creek watershed that remains as native forest or prairie (grassland) is greater than 60% for most sub-basins (Table 20). The entire watershed is only 19% impervious and retains 70% of the native forest or prairie land-cover. As a result, Muck Creek is generally on the lower end of the watershed impact scale. In most cases, very little of the forested area is dominated by the mature coniferous species that are native to the region. In addition, only a fraction of the original native SPSP ecosystem is left intact, although almost all of the total remaining SPSP in the Muck Creek watershed is located on Fort Lewis. Open military training areas and artillery impact areas, however, do have an impact on Muck Creek within the Fort Lewis boundaries. These areas tend to be dominated by herbaceous vegetation, shrubs, and various invasive and exotic species. In another respect, the requirements of military training operations are beneficial to maintaining the SPSP ecosystem, in that forest encroachment is not desirable for either.

The lower segments of Muck Creek can be characterized as typical of PSL streams. From the confluence with the Nisqually River to the end of Ellsworth Woods (Figure 28), the stream has a pool-riffle morphology. The riparian corridor is also typical of PSL streams, with a mixed coniferous forest being the dominant vegetation. There are also extensive off-channel wetlands and beaver ponds throughout this section of the creek, both characteristic features of natural PSL stream ecosystems.

The middle and upper sections of the Muck Creek landscape are more typical of the SPSP ecosystem. There is also minimal natural riparian forest within the riparian corridor of most of the stream channels within the upper watershed. Herbaceous vegetation is dominant, with patches of oak and pine also present. Riparian areas where natural forest remains are typically dominated by low deciduous species including red alder, willow, and big-leaf maple. Mature, mixed riparian corridors still occur in isolated areas in the middle watershed. For the most part, the artillery impact area has had little negative effect on the lower Muck Creek corridor. The riparian buffers in the lower watershed are generally adequate, with little fragmentation by roads or trails. In the upper watershed, “maneuver areas” and “tank fords” have had an impact on the stream-riparian corridor, but intact patches remain.

It is difficult to say exactly what the original SPSP riparian corridors looked like. Off-channel and instream wetlands likely were an important feature, retaining water through the dry summer period, while sections of the streambed became dry as water infiltrated into the permeable glacial outwash soils. The nearby Scatter Creek Nature Conservancy Preserve has many of these characteristics. There are still extensive wetland areas throughout the middle and upper Muck Creek watershed, but many of these have been modified with outlet structures or drained for agricultural land-use. In addition to the loss of wetlands, the historical agricultural land-use also resulted in several sections of the stream being channelized. This is easily seen in the segment upstream of Ellsworth Woods, adjacent to the impact area and in the upper watershed upstream of SR-507.

Basin Land-use

- Table 20 summarizes the land-cover and land-use data for the watershed. Fort Lewis, as a whole, is approximately 25% impervious, including the roads, parking areas, buildings, the helicopter airfield, and associated flightlines.
- Road density within Fort Lewis is only 3.3 km/km^2 and is only 2.2 km/km^2 in the area contributing to Muck Creek. Generally, a road density over 3 km/km^2 is considered high and is expected to have a significant impact on aquatic resources (*May et al*., 1997).
- Grass/lawn and landscaped areas dominate the developed portions of the base. The cantonment area contains almost 90% of the imperviousness on base. The "impact areas" are also almost entirely grassland.
- Relatively large areas of native prairie, wetland, and forest still exist on the base. These areas contain remnants of native flora and fauna, including several endangered species. DoD and The Nature Conservancy of Washington are jointly managing these areas.

Stream Survey Reach Descriptions

- Stream survey reaches are delineated on Figure 28.
- Table 21 summarizes the segments of Muck Creek and its main tributaries (Johnson and Lacamas creeks) that were surveyed during this project.
- Data summary maps for riparian conditions, salmonid habitat, and biological integrity are included in Appendix G.

Table 21. *Muck Creek stream survey reach descriptions (see Appendix G maps)*

MCK-1	Lower mainstem, from Nisqually confluence, upstream approximately 0.5 miles.
Riparian is dominated by mature mixed and native shrub, principally vine maple. Streambed is primarily large cobble.	
MCK-2	Lower mainstem, from 1.8 miles below first crossing, continuing upstream 0.7 miles.
Canopy open slightly, and stream banks are steep. Bed material alters to large gravel. Riparian is primarily mature evergreen, mixed, and deciduous.	
MCK-3	Lower mainstem,beaver-ponds and riparian wetlands (spring-fed). Beginning about stream mile 2.5 and continuing for 1.0 mile.
Streambed material is mainly gravel, and banks are steep, very eroded in places. Riparian continues to be mature evergreen with a mixture of mature deciduous and shrub. Off channel wetlands dominate the riparian corridor.	

MCK-4 Lower mainstem, above second crossing at Ellsworth Woods, from mile 3.5. Length is approximately 0.8 miles

Ellsworth Woods riparian is mature evergreen, mixed, deciduous, and shrub. Streambed is mainly gravel. Riparian wetlands continue to be common.

MCK-5 Lower mainstem, parallel to impact area access road, mile 4.3 to 4.9. Total length about 0.6 miles.

The mature forest is lost after Ellsworth Woods. Mostly young trees, tall herbaceous, and shrub. Riparian wetlands continue to be common. Streambed is mainly gravel.

MCK-6 Middle mainstem, from mile 5.5, parallel to impact area (begins about 0.5 to 0.6 miles below the bridge), to 0.3 or 0.4 above the bridge at Roush Marsh. (Split channel). Total length approximately 1.0 mile.

Riparian wetlands dominate the stream corridor. From this point to the upstream marshes, riparian is young trees, shrub, and herbaceous. Streambed is mainly silt.

MCK-7 Middle mainstem, Roush Marsh to Roy. Begins downstream of the town, 0.2-0.25 miles from the bridge on 507, and runs through town to Muck Lake wetland area. Total of about 0.4 to 0.5 miles

Riparian is a mixture of trees, shrub, tall herbaceous, and low herbaceous or landscaped areas. Encroachment by development is common. Streambed is mainly silt.

MCK-8 Middle mainstem, above Roy (about 0.4 miles from end of last reach) and 0.2 miles below Chambers Lake.

Riparian is a mixture of mixed mature forest, patches of young deciduous trees, shrub, and herbaceous vegetation. Exotics vegetation is also present. Streambed is mainly silt.

MCK-9 North fork below south tank ford.

Riparian is mainly South Puget Sound Prairie vegetation, including mature oak, grassland, and shrub. Douglas fir, invasives, and exotic vegetation are also present.

MCK-10 North fork above south tank ford. Begins at the tank ford, runs only 0.2 to 0.3 miles.

Riparian is mainly South Puget Sound Prairie grassland with patches of evergreens and shrubs.

MCK-11 North fork crossing at 8th Ave. About a 0.2-mile segment of this reach is on base. It begins inside the base, 0.2 miles west of 8th Ave. boundary fence, and continues for 0.4 miles on non-military property.

Riparian is mainly South Puget Sound Prairie vegetation, including mature oak, patches of evergreens, prairie grassland, and shrub.

JSN-1 Lower section, above confluence with Muck Creek. From crossing East Gate Road, downstream perhaps 0.1 to 0.15 miles.

Riparian zone is mature evergreen, mixed, deciduous, and shrub. Streambed is mainly gravel. Riparian wetlands are common.

LAC-1 Lower section, above confluence with Muck Creek.

Riparian zone is mature evergreen, mixed, deciduous, and shrub. Streambed is mainly gravel. Riparian wetlands are common. Invasive and exotic vegetation are also present.

Note: Muck Creek was dry, from below SR-507 to where the creek branches, during the survey period**.**

Riparian Corridor Continuity

- MCK-1: The riparian corridor is intact, with no fragmentation. The site of an old bridge is located near the mouth of the creek, but the remaining foundations are causing minimal impact on the stream.
- MCK-2: The riparian corridor is relatively intact, with minimal fragmentation (two road crossings).
- MCK-3: The riparian corridor is relatively intact, with minimal fragmentation (one road crossing).
- MCK-4: The riparian corridor is relatively intact, with minimal fragmentation (two road crossings).
- MCK-5: The riparian corridor is narrow and fragmented by several road or trail crossings, as well as gaps in riparian vegetation due to past land-use activities.
- MCK-6: The riparian corridor is narrow and fragmented. The stream is mostly riparian wetland habitat in this segment. One major road crossing exists in this segment, but the corridor lacks riparian vegetation for much of its length.
- MCK-7: The riparian corridor is narrow and fragmented by several road crossings within the town of Roy. Little natural riparian corridor remains.
- MCK-8: The riparian corridor is relatively intact, with minimal fragmentation (two road crossings).
- MCK-9: The riparian corridor is narrow in most places and is partially SPSP and part forested riparian. SR-507 crosses the stream at the start of this segment and two tank fords also cross the creek.
- MCK-10: The riparian corridor is narrow in most places and is mostly SPSP. There are two tank fords that cross the creek in this segment.
- MCK-11: The riparian corridor is narrow in most places and is mostly SPSP. The Fort Lewis boundary road (8th Ave.) crosses the creek in this segment.
- JSN-1: The riparian corridor is relatively intact, with minimal fragmentation (one road crossing).
- LAC-1: The riparian corridor is relatively intact, with minimal fragmentation (three road crossings).

Riparian Integrity

- MCK-1: The riparian forest is a mixture of mature conifers and deciduous trees with a well-established understory and groundcover layers. The riparian zone is wide and intact. LWD recruitment potential is rated as good to excellent. Riparian integrity is high for this segment.
- MCK-2: The riparian forest is predominately mixed forest (both mature and young) with a well-established understory and groundcover layers. The riparian zone is wide and intact. LWD recruitment potential is rated as good to excellent. Riparian integrity is high for this segment.
- MCK-3: The riparian forest is a mixture of mature conifers and deciduous trees with a well-established understory and groundcover layers. The riparian zone is wide and relatively intact. LWD recruitment potential is rated as good. Riparian integrity is moderate for this segment.
- MCK-4: The riparian forest is predominately mixed mature forest (Ellsworth Woods), with a well-established understory and groundcover layers. The riparian zone is wide and relatively intact. LWD recruitment potential is rated as good. Riparian integrity is high for this segment.
- MCK-5: The riparian zone is narrow and fragmented. The stream has also been channelized in several reaches of this segment and encroachment from the impact area is evident. Young trees, shrubs, and herbaceous prairie vegetation dominate the riparian zone in this segment. Riparian integrity is low for this segment.
- MCK-6: The riparian zone is narrow and open. The stream has also been channelized in several reaches of this segment and encroachment from the impact area is evident. Wetland vegetation, shrubs, and herbaceous prairie vegetation dominate the riparian zone in this segment. Riparian integrity is low for this segment.
- MCK-7: The riparian zone is narrow and fragmented. The stream has also been channelized in several reaches of this segment and encroachment from the town of Roy is severe in most reaches. Young trees, shrubs, and landscaping dominate the riparian zone in this segment. Riparian integrity is low for this segment.
- MCK-8: The riparian forest is mainly mature coniferous forest and young deciduous, with a well-established understory and groundcover layers. The riparian zone is narrow, but is relatively intact. LWD recruitment potential is rated as good to excellent. Riparian integrity is high for this segment.
- MCK-9: The riparian zone is narrow and open. The stream has also been channelized in several reaches of this segment, although encroachment from the training areas is minimal. Some trees and wetland vegetation, shrubs, and herbaceous prairie vegetation dominate the riparian zone in this segment. LWD recruitment potential is rated as poor. Riparian integrity is low for this segment.

- MCK-10: The riparian zone is narrow and open. The stream has also been channelized in several reaches of this segment, although encroachment from the training areas is minimal. Some trees and wetland vegetation, shrubs, and herbaceous prairie vegetation dominate the riparian zone in this segment. LWD recruitment potential is rated as poor. Riparian integrity is low for this segment.
- MCK-11: The riparian zone is narrow and open. The stream has also been channelized in several reaches of this segment, although encroachment from the training areas is minimal. Some trees and wetland vegetation, shrubs, and herbaceous prairie vegetation dominate the riparian zone in this segment. LWD recruitment potential is rated as poor. Riparian integrity is low for this segment.
- JSN-1: The riparian forest is mainly mature coniferous forest and young deciduous, with a well-established understory and groundcover layers. The riparian zone is wide and relatively intact. LWD recruitment potential is rated as good to excellent. Riparian integrity is high for this segment.
- LAC-1: The riparian forest is predominately deciduous forest (both mature and young). The riparian zone is narrow, but relatively intact. LWD recruitment potential is rated as fair. Riparian integrity is moderate for this segment.

Canopy Cover

- MCK-1: Although the riparian zone is dominated by mature forest, the canopy cover is relatively open in this reach. The creek is quite wide near the confluence and a closed canopy is not expected in this situation. As a result of the natural light, instream macrophytes, moss, and other aquatic vegetation is common.
- MCK-2: Although the riparian zone is dominated by mature forest, the canopy cover is relatively open in this reach.
- MCK-3: The riparian zone is dominated by mixed-mature forest and the canopy cover is relatively closed in this reach.
- MCK-4: The riparian zone is dominated by mixed-mature forest and the canopy cover is relatively closed in this reach.
- MCK-5: The riparian zone is mostly wetland and prairie vegetation and, as a result, the canopy cover is almost entirely open in this segment of the creek.
- MCK-6: The riparian zone is mostly wetland and prairie vegetation and, as a result, the canopy cover is almost entirely open in this segment of the creek.
- MCK-7: The riparian zone is patchy and canopy cover is almost relatively open in this segment of the creek.
- MCK-8: The riparian zone is dominated by mature forest and the canopy cover is relatively closed in this segment.

- MCK-9: The riparian zone is mostly prairie vegetation and, as a result, the canopy cover is almost entirely open in this segment of the creek.
- MCK-10: The riparian zone is mostly prairie vegetation and, as a result, the canopy cover is almost entirely open in this segment of the creek.
- MCK-11: The riparian zone is mostly prairie vegetation and, as a result, the canopy cover is almost entirely open in this segment of the creek.
- JSN-1: The riparian zone is dominated by mature forest and the canopy cover is relatively closed in this segment.
- LAC-1: The riparian forest is predominately deciduous forest (both mature and young) and the canopy cover is relatively open in this segment.

Large Woody Debris

LWD is a key structural feature in PNW streams. LWD is the main pool-forming element in lowland streams and is responsible for much of the natural channel complexity in these streams (*Maser et al*., 1988). The desired frequency of LWD for PFC is > 400/km, with < 200/km considered inadequate. This equates to a normalized target BFW-spacing of 2 pieces of LWD per BFW-length of stream channel (*Peterson et al*., 1992). Large, key pieces of LWD are especially important because they are relatively stable and provide long-term habitat as well as instream cover for salmonids. The PFC target for key LWD is generally considered to be >50/km or about 25% of the total LWD.

- MCK-1: Almost all the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was within the desired range for PFC and the BFW-spacing was almost double the target value. The average size of instream LWD was also within the range expected for natural stream channels. However only 15% of the LWD was classified as key and only one-third of the LWD was coniferous. Channel complexity was generally good in this segment. LWD recruitment potential is also good. The lack of adequate key LWD and the dominance of deciduous LWD are the most significant deficiencies.
- MCK-2: Almost all the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, but the BFW-spacing was above the target. The average size of instream LWD was also within the range expected for natural stream channels, but only 35% of the LWD was classified as key. On the positive side, a majority of the LWD (65%) was coniferous. Channel complexity was generally good in this segment. LWD recruitment potential is also good. The lack of adequate key LWD and the low quantity of instream LWD are the most significant deficiencies in this segment.
- MCK-3: Almost all the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was within the desired range for PFC and the BFW-spacing was almost double the target value. The average size of instream LWD was also within the range expected for natural stream channels, however only about 5% of the LWD was classified as key and only

one-third of the LWD was coniferous. Channel complexity was generally good in this segment, but LWD recruitment potential was found to be low. The lack of adequate key LWD and the dominance of deciduous LWD are the most significant deficiencies in this segment. Beaver ponds and wetlands were common throughout the segment.

- MCK-4: All the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels and only about 5% of the LWD was classified as key. On the positive side, a majority of the LWD (60%) was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The lack of adequate key LWD and the low quantity of instream LWD are the most significant deficiencies in this segment. Beaver ponds and wetlands were common throughout the segment.
- MCK-5: All the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels and only about 5% of the LWD was classified as key. In addition, almost none of the LWD was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The lack of adequate key LWD and the low quantity of instream LWD in general are the most significant deficiencies in this segment.
- MCK-6: There was little LWD found in this segment. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels and none of the LWD was classified as key. In addition, none of the LWD was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The lack of adequate key LWD and the low quantity of instream LWD in general are the most significant deficiencies in this segment. Riparian wetlands were common throughout the segment.
- MCK-7: All the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels and about 20% of the LWD was classified as key. In addition, only about 20% of the LWD was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The lack of adequate key LWD and the low quantity of instream LWD in general are the most significant deficiencies in this segment.
- MCK-8: All the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired

range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels and only about 10% of the LWD was classified as key. On the positive side, a majority of the LWD (67%) was coniferous. Channel complexity was generally only fair in this segment, as was LWD recruitment potential. The lack of adequate key LWD and the low quantity of instream LWD are the most significant deficiencies in this segment.

- MCK-9: All the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels, but over 40% of the LWD was classified as key. In addition, a majority of the LWD (63%) was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The low quantity of instream LWD is the most significant deficiency in this segment.
- MCK-10: No LWD was surveyed in this segment, which had a riparian zone that was predominantly prairie habitat. The lack of LWD may not be a significant problem for SPSP streams.
- MCK-11: Almost all the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels and none of the LWD was classified as key LWD. In addition, none of the LWD was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The lack of adequate key LWD and the low quantity of instream LWD are the most significant deficiencies in this segment. The lack of LWD may not be a significant problem for SPSP streams.
- JSN-1: All the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels and only about 5% of the LWD was classified as key. In addition, almost none of the LWD was coniferous. Channel complexity was generally moderate in this segment and LWD recruitment potential was good. The lack of adequate key LWD and the low quantity of instream LWD, especially coniferous, are the most significant deficiencies in this segment.
- LAC-1: Almost all the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels and none of the LWD was classified as key. In addition, none of the LWD was coniferous. Channel complexity was generally low in this segment, as was LWD

recruitment potential. The lack of adequate key LWD and the low quantity of instream LWD are the most significant deficiencies in this segment.

Rearing Habitat

Rearing habitat typically mirrors the quantity and quality of LWD in the stream channel. PQI scores indicate the quality of rearing habitat in each pool. High quality pools are generally deep, large in size, and have abundant cover (LWD, overhanging vegetation, etc.). The NMFS MPI suggests 60–80 pools/km for PFC in streams with a bankfull width of 5–10 m. Pool BFW-spacing should be less than 2 (*Peterson et al*., 1992). In addition, the % pool habitat (by surface area) should be 40–60% for low gradient streams, such as the lowland streams in this study. RPD should be relatively deep to provide good cover and temperature refugia.

- MCK-1: Pool frequency, pool BFW-spacing, and the % pool habitat (8.2%) were all well below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally good (PQI = 3.71).
- MCK-2: Pool frequency, pool BFW-spacing, and the % pool habitat (4.2%) were all well below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally good (PQI = 3.50).
- MCK-3: Pool frequency and the % pool habitat (28.4%) were below the MPI-target range. BFW pool-spacing was within the desired range (<2). The average RPD was relatively shallow. However, the quality of pools in this segment was generally good (PQI = 3.44).
- MCK-4: Pool frequency, pool BFW-spacing, and the % pool habitat (20%) were all well below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally good (PQI = 4.00).
- MCK-5: Pool frequency, pool BFW-spacing, and the % pool habitat (28%) were all below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally good (PQI = 4.00).
- MCK-6: Pool frequency, pool BFW-spacing, and the % pool habitat (2%) were all well below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally good (PQI = 4.00).
- MCK-7: Pool frequency, pool BFW-spacing, and the % pool habitat (19%) were all below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally fair (PQI = 2.57).
- MCK-8: Pool frequency, pool BFW-spacing, and the % pool habitat (19%) were all below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally poor (PQI = 2.00).

- MCK-9/10/11: No pools were noted in these survey segments.
- JSN-1: Pool frequency, pool BFW-spacing, and the % pool habitat (25.6%) were all below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally fair (PQI = 2.25).
- LAC-1: Pool frequency, pool BFW-spacing, and the % pool habitat (37%) were all below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally fair (PQI = 2.57).

Spawning Habitat

RQI scores indicate the quality of spawning habitat in each riffle. High quality riffles have clean substrate, low embeddedness, and abundant instream cover. In addition, the % riffle habitat (by surface area) should be 40–50% for low gradient streams, such as these lowland streams.

- MCK-1: Spawning habitat quantity (72%) and quality (RQI = 3.0) were both within the PFC range in this survey segment.
- MCK-2: Spawning habitat quantity (75%) and quality (RQI = 2.0) were both within the PFC range in this survey segment.
- MCK-3: Spawning habitat quantity (44%) and quality (RQI = 3.3) were both within the PFC range in this survey segment.
- MCK-4: Spawning habitat quantity (17%) was below the PFC range, but quality (RQI = 3.6) was within the PFC range in this survey segment.
- MCK-5: Spawning habitat quantity (13%) was below the PFC range, but quality (RQI = 3.2) was within the PFC range in this survey segment.
- MCK-6: Spawning habitat quantity (5%) and quality (RQI = 1.0) were both below the PFC range in this survey segment.
- MCK-7: Spawning habitat quantity (12%) was below the PFC range, but quality (RQI = 3.0) was within the PFC range in this survey segment.
- MCK-8: Spawning habitat quantity (18%) and quality (RQI = 2.0) were both below the PFC range in this survey segment.
- MCK-9/10/11: Spawning habitat quantity and quality were below the PFC range in these survey segments.
- JSN-1: Spawning habitat quantity (53%) and quality (RQI = 3.5) were both within the PFC range in this survey segment.
- LAC-1: Spawning habitat quantity (6%) was below the PFC range, but the quality (RQI = 3.0) was within the PFC range in this survey segment.

It should be noted that the lower reaches of Muck Creek (MCK-1, 2, and 3 are the predominate spawning areas for chum salmon within the creek. Therefore, the dominance of riffle habitat over pools is not that significant of a factor. This is because chum salmon

do not rear in the stream for a significant time period and thus require little pool habitat. On the other hand, coho salmon, which do rear in the stream for an extended period, do require adequate pool habitat. Coho mainly utilize the middle and upper reaches of Muck Creek.

Habitat Quality Index (HQI)

The habitat quality of the assessed segments of Muck Creek on Fort Lewis (see Appendix G – data maps) was evaluated using the HQI. The summed score of eight metrics determined the final HQI score (see Results for details). In addition, streambank stability was generally found to be good throughout Muck Creek, indicating that excessive stormflows are not a major watershed problem.

- MCK-1: HQI = 31 (good)
- MCK-2: HQI = 25 (fair)
- MCK-3: HQI = 38 (good)
- MCK-4: HQI = 24 (fair)
- MCK-5: HQI = 13 (poor)
- MCK-6: HQI = 8 (poor)
- MCK-7: HQI = 13 (poor)
- MCK-8: HQI = 13 (poor)
- MCK-9: HQI = 16 (poor)
- MCK-10: HQI = 8 (poor)
- MCK-11: HQI = 11 (poor)
- LAC-1: HQI = 13 (poor)
- JSN-1: HQI = 29 (fair)

Biological Integrity

- In general, the biological integrity of Muck Creek and its tributaries was found to be within the natural range.
- MCK-1: B-IBI Score = 42 (Good)
- MCK-2: B-IBI Score = 36 (Good)
- MCK-3: Not Sampled
- MCK-4: B-IBI Score = 24 (Poor)
- MCK-5: Not Sampled
- MCK-6: Not Sampled
- MCK-7: Not Sampled
- MCK-8: Not Sampled

- MCK-9: Not Sampled
- MCK-10: Not Sampled
- MCK-11: B-IBI Score = 36 (Good)
- JSN-1: B-IBI Score = 28 (Fair)
- LAC-1: B-IBI Score = 30 (Fair)
- LAC-2: B-IBI Score = 36 (Fair)

Chemical Water Quality

This study did not specifically assess chemical water quality.

Photographs

See Appendix L for pictures of Muck Creek on Fort Lewis.

Recommendations

1. The lower segments of Muck Creek (MCK-1, 2, 3, and 4 below Ellsworth Woods) are in a relatively natural condition. This is very likely due to the minimal human activity that takes place in these segments based on their location within the artillery impact area safety zone. The riparian corridor is relatively intact, quite wide (> 100 meters in most of the corridor), and dominated by mature forest. Beaver activity is common, with several ponds and wetland areas providing excellent salmonid rearing habitat. There is very little streambank erosion or streambed scour, resulting in good spawning habitat throughout the lower segments of the creek. Conservation and enhancement of this refugia area should be the primary strategy for aquatic resource management within lower Muck Creek. It is recommended that stewardship of this section of Muck Creek include the following:
    - Installation of a flow gage at the mouth of Muck Creek to monitor changes in the hydrologic regime.
    - Continue with short-term LWD enhancement projects at select locations within lower Muck Creek.
    - Continue long-term riparian plantings of native cedar, hemlock, cottonwood, and spruce. Restore natural riparian function throughout watershed.
    - Continue spawning gravel enhancement projects at selected locations in lower Muck Creek.
    - Removal and restoration of all non-essential stream crossings and roads within 100 m of the stream
    - Continue with the exotic vegetation management program currently in existence at Fort Lewis.
2. Prior to human modification, the middle reaches of Muck Creek were likely a mixture of wetlands, SPSP, and coniferous-dominated forest habitats. This section of the creek (from Ellsworth Woods to SR-507) has been impacted by human land-use activity more than any other section of the creek. This includes historic agriculture,

U.S. Army operations, and development in the town of Roy. The Johnson and Lacamas creek tributaries are also included in this section of Muck Creek. It is recommended that a landscape assessment be conducted to determine which areas were originally SPSP and which forested or wetland habitat. Each of these areas will require a unique management strategy, but there are several common elements with respect to the aquatic ecosystems within each:

- Continue with the wetland restoration and water management program on Fort Lewis. Restore natural wetland function throughout watershed.
- Continue with short-term LWD enhancement projects at select locations within middle Muck Creek.
- Continue long-term riparian plantings of native cedar, hemlock, cottonwood, and spruce.
- Conserve native forest and prairie cover throughout the watershed and minimize impervious surfaces in all developed areas.
- Restore floodplain function and stream channel migration zone. Protect stable natural hydrology, including protecting the integrity of the very large beaver dam complexes in the watershed.

3. The upper reaches of Muck Creek on Fort Lewis appear to have characteristics typical of SPSP streams. Little research has been done on the SPSP ecosystem in general (see Appendix D) and almost nothing is known about the SPSP streams and wetlands. It is recommended that research be conducted to better understand these unique aquatic systems and that the upper portion of Muck Creek (upstream of the SR-507 crossing) by restored to a natural SPSP stream-wetland ecosystem. This should have a minimal impact on military operational training and may actually enhance the training environment because it is likely that most of the existing Douglas fir stands will need to be removed to prevent succession of the prairie environment. The one training related area that needs to be addressed in this section of the watershed is the design of current and future tank fords. Although primarily localized in their impact, these “low-water” crossings can have a significant impact on the streambed and can result in downstream siltation if not properly constructed and maintained. The ITAM program at Fort Stewart (GA) has developed a low-water crossing design that minimizes impact to the stream and is low maintenance (Figure 29). This design uses a Geo-Grid foundation filled with washed gravel or river rock and is designed to replicate a natural streambed while supporting tracked vehicles during periodic crossings. The design has been very successful at Fort Stewart and several other military installations in the Southeast. It is recommended that the Fort Lewis ITAM program investigate the use of this design for all current and future tank fords.
4. Muck Creek is sensitive to loss of surface baseflow during the summer dry season in the PNW. Because of this and the potential impacts on aquatic biota when sections of the creek become hyporheic, any modification of wetland or lake level can have serious downstream consequences. It is recommended that the hydrology of the creek be studied in depth and that a hydrologic management strategy be developed that

mimics that natural watershed hydrologic regime. This should include evaluation of any water level controls (e.g., Chambers Lake, Johnson Marsh, etc.). Wetland conservation and restoration will likely be an important element of any future watershed strategy in Muck Creek. In addition, beaver activity should be considered in their role as a potential keystone species in the watershed. A recently published WA-DOE report (*Sinclair*, 2001) summarizes the current state of knowledge with regard to surface flow and groundwater interactions in the Muck Creek watershed. The report indicates that historic land-use practices, such as channelization of streams and draining of wetlands for agriculture may have exacerbated the natural surface water loss in the central Muck creek basin, but the magnitude of these impacts is difficult to quantify (*Sinclair*, 2001). In addition, it is likely that current military activities, such as operational training and tank fords have had a minimal impact on the natural hydrogeology of the central Muck Creek basin. Based on this information, it is recommended that Fort Lewis continue programs designed to enhance native wetland and prairie ecosystems in the training areas of the base. In addition, the impact of military operations on stream crossings and wetland encroachment be minimized using the measures discussed above.

5. The Fort Lewis portion of the Muck Creek watershed is generally undeveloped, with the primary land-use activity being military training. This training includes tracked vehicle maneuvers, infantry exercises, and artillery firing within the impact area. With adequate buffers around the stream-riparian corridor and the use of low-impact designs for stream crossings, these military-unique activities (see Appendix A) can be conducted with minimal impact to the stream ecosystem.

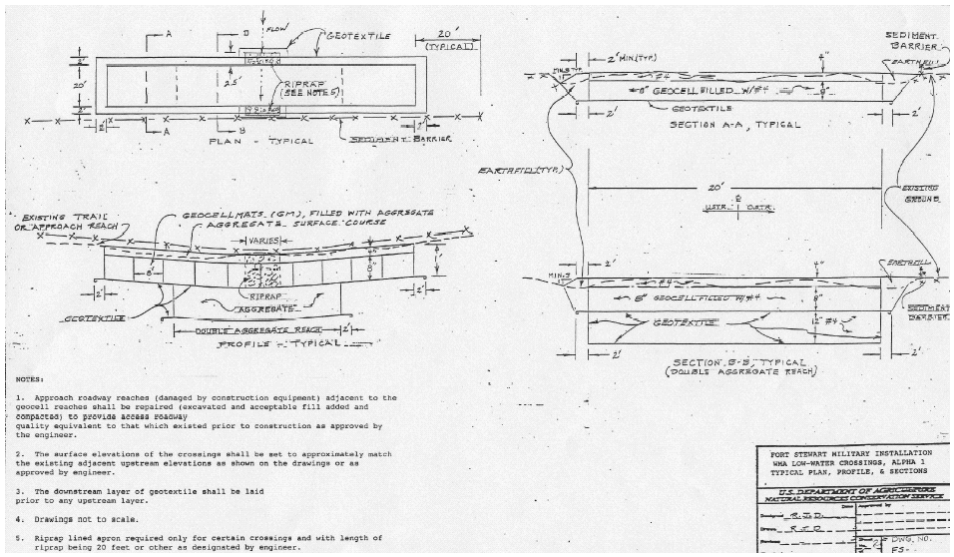

Figure 29. *Fort Stewart ITAM low-water crossing design*

Murray Creek

Murray Creek lies wholly within the boundaries of Fort Lewis, McChord AFB, and Camp Murray although a large majority of the sub-basin is within the Madigan Army Medical Center (MAMC) area of Fort Lewis. The Murray Creek sub-basin also includes the Fort Lewis Logistics Center and the Evergreen housing complex. The creek originates in Kinsey Marsh, a headwater wetland located at the north end of Fort Lewis (with a small portion within the southern area of McChord AFB). The creek flows through the Madigan section of Fort Lewis before crossing under Interstate-5 (I-5) and then passes through Camp Murray, Army National Guard Center before emptying into American Lake (Figure 30). Murray Creek supports a native population of cutthroat trout and is also utilized for spawning by kokanee salmon from American Lake (*Fort Lewis*, 1996). Although the Murray Creek watershed is highly developed (36% TIA) and has only a fraction of its original native land-cover (see Table 20), the creek retains a measure of ecological integrity and should be considered a valuable natural resource area. The primary impacts to Murray Creek are encroachment by surrounding development, fragmentation of the stream-riparian corridor by road crossings, and stormwater run-off from impervious surfaces within the watershed (*Fort Lewis*, 1996). The main features of the creek that have helped maintain its current level of ecological integrity include the extensive, mostly intact headwater wetlands that still exist and its nearly continuous riparian buffer zone.

The 1996 study of Murray Creek found that the lower creek was prone to drying during late summer when baseflow conditions are most critical in the PSL region. The headwater and off-channel wetlands of Murray Creek are critical to maintaining this baseflow. The groundwater within the watershed is primarily contained within the surface aquifer.

Activities in the watershed that reduce groundwater and wetland recharge were found to have potentially significant impact on the baseflow of Murray Creek (*Fort Lewis*, 1996). These potentially harmful activities include groundwater pumping, stream channelization, and increasing impervious surface area within the basin. Pumping activities at MAMC were found to be a significant impact on flow conditions in the creek (*Fort Lewis*, 1996).

The MAMC complex and the Fort Lewis Logistic Center also have significant areas of impervious surface (see Table 20). Approximately 18% of the watershed is impervious surface (roads, rooftops, and parking lots). This is a significant fraction of the watershed area and has resulted in less groundwater recharge and more stormwater run-off (*Fort Lewis*, 1996). Reducing impervious surface areas and increasing infiltration of surface run-off are two of the most important actions that can be taken in the Murray Creek watershed to maintain the natural hydrologic flow regime within the creek. The use of permeable pavement and other porous surfaces (gravel) are strongly recommended for parking lots and low-traffic roads. In addition, biofiltration swales, infiltration basins/trenches, and constructed wetlands are recommended for stormwater treatment. The soils in much of the Murray Creek basin are highly suitable for infiltration (*Fort Lewis*, 1996). Probably the most important action that can be taken is the conservation of natural vegetation cover (forest and prairie). Currently only about 30% of the basin area is natural forest or grassland cover (see Table 20). Because of the many critical functions it provides, the retention of native forest is particularly important within the riparian corridor of the stream. There are currently 12 stream crossings along Murray Creek from its headwaters to the mouth. This works out to be approximately 2 crossings per km of stream channel length, which is considered moderately detrimental in that it results in fragmentation of the stream-riparian ecosystem (*May et al.*, 1997). Most of these crossings utilize culverts. While none of these are currently judged to be passage barriers for salmonids, all are potential barriers if flow conditions are outside the normal range. Murray Creek and its riparian corridor also have a significant invasive plant problem; reed canary grass is the greatest. Fort Lewis has an active rehabilitation program underway in the upper Murray Creek watershed. Efforts include riparian vegetation restoration, spawning gravel enhancement, and an on-going invasive plant control program to eliminate reed canary grass and other exotic species from the stream-riparian corridor. In addition, extensive riparian buffer enhancement work has been done around the Kinsey Marsh headwater wetlands and one road crossing was removed to reduce fragmentation of the stream-wetland ecosystem.

Figure 30. *Fort Lewis Army Base, showing the Murray Creek and Sequalitchew Creek watersheds*

Sequalitchew Creek

Sequalitchew Creek is located within the north Fort Lewis area of the base (Figure 30). The creek originates in Sequalitchew Lake and Hunter Marsh, then flows through Edmond Marsh, before flowing into Puget Sound below Dupont, WA. Sequalitchew Springs, adjacent to the lake, is a primary source of drinking water for Fort Lewis.

Much of the stormwater run-off from the cantonment area is routed, via treatment facilities, to Hunter Marsh. To prevent this run-off from flowing into Sequalitchew Lake and to minimize its impact on the downstream segments of the creek, a diversion structure has been constructed at the outlet of the lake (Figure 31). Run-off is diverted directly to Puget Sound via an unlined drainage channel (Figure 30). Edmond Marsh has also been significantly degraded and hydrologically modified by off-base development in the Dupont area. As a result of these impacts, lower Sequalitchew Creek is basically disconnected from the upper watershed and frequently goes dry in late summer.

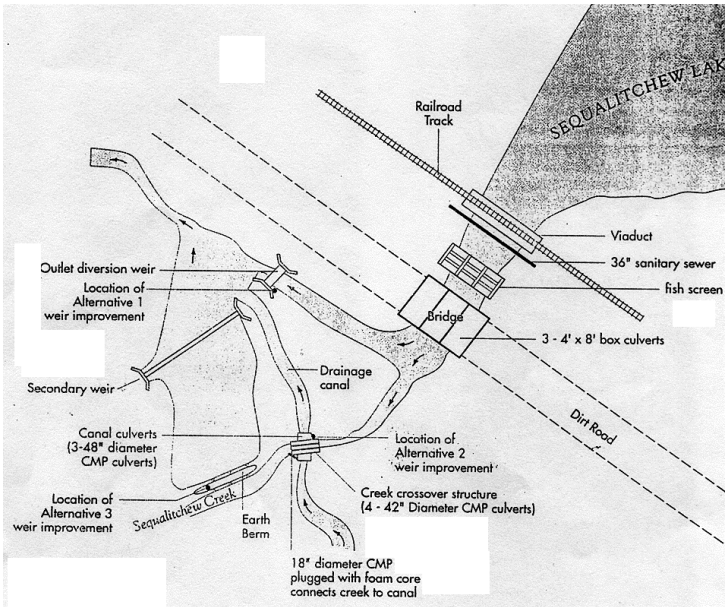

Figure 31. *Sequalitchew Lake outlet and stream diversion structure (Fort Lewis, 1996)*

Stream Data Analysis

Watershed Characterization

The percentage of the Murray Creek watershed that remains as native forest or prairie (grassland) is approximately 30% (Table 20). In most cases, very little of the forested area is dominated by the mature coniferous species that are native to the region. In addition, very little of the native SPSP ecosystem is left intact. Landscaped areas, herbaceous vegetation, shrubs, and various exotics characterize the majority of vegetated areas within the watershed. There is also minimal mature riparian forest within the riparian corridor of most of the stream channels within the watershed. Murray Creek watershed has a total impervious area of 36% (Table 20), placing it in a category where stormwater run-off and potential water quality problems are of significant concern.

Basin Land-use

- Table 20 summarizes the land-cover and land-use data for the watershed.
- Road density in the Murray Creek watershed is approximately 3.8 km/km^2. Generally, a road density over 3 km/km^2 is considered high.
- Grass/lawn and landscaped areas dominate the developed portions of the base.
- The Sequalitchew Creek watershed is dominated by suburban levels of residential and commercial land-use, with a total impervious area of 36% TIA.

Riparian Corridor Continuity

- Total number of stream crossings on Murray Creek is 12 or 2 crossings per km of stream. This is considered moderate and is indicative of the fragmented nature of the stream-riparian corridor.

- Interstate-5 is the largest single stream crossing, with three 36" culverts providing passage under the highway. This culvert, although quite long, is passable by both adult and juvenile salmonids. Five other culverted crossings exist on Murray Creek, none of which are salmonid migration barriers at this time.
- Lower Sequalitchew Creek is relatively intact. The creek is located in a deep ravine, with no crossings. However, there is an operational rail line that runs parallel to the creek within the stream-riparian corridor. This railroad line was built during World War II to carry explosives from the Dupont manufacturing facilities to loading docks on Puget Sound. The location of the railroad grade disrupts some riparian corridor function and has resulted in several small hillslope failures that have delivered sediment into the creek.

Riparian Integrity

- The riparian zone of Murray Creek on Fort Lewis is relatively intact, although it is dominated by young deciduous vegetation. Much of the stream corridor above the I-5 crossing is riparian wetland. Patches of coniferous and mixed forest exist in the upper riparian corridor as well (Appendix H).
- Riparian vegetation often includes exotic/invasive species such as Himalayan blackberry (*Rubus discolor*), reed canary grass (*Phalaris arundinacae*), and Japanese knotweed (*Polygonum cuspidatum*).
- The riparian corridor of lower Sequalitchew Creek, although relatively wide and intact, is lacking in mature conifers (Appendix H).

Canopy Cover

- The upper Murray Creek survey reach (segment MRY-2) was rated low for canopy cover (Appendix H). Although the creek has a relatively open canopy, there is sufficient cover and shade to maintain suitable temperature conditions in most of the creek.
- The lower mainstem (segment MRY-1) of the creek (below I-5) is generally shaded, but the riparian zone is encroached upon by development on Camp Murray. The zone just above the mouth on American Lake is well forested.
- The canopy cover of lower Sequalitchew Creek is generally "good-excellent" (Appendix H).

Large Woody Debris

- No segments of Murray Creek contained LWD within the PFC range identified in the current scientific literature. In fact, there was little functional LWD found in the entire length of the creek within the base (Appendix H). In addition, that LWD that was surveyed in the lower reach was mostly in the form of installed log weirs that provided poor functional habitat value.
- The lack of mature, coniferous forest within the riparian corridor of Murray Creek also makes LWD recruitment potential within these segments poor (Appendix H).

- Lower Sequalitchew Creek has adequate LWD (although most of the instream LWD is deciduous) and has a good LWD recruitment potential (Appendix H).

Channel Morphology

- Below I-5, the Murray Creek channel is narrow and moderately confined. It is also moderately entrenched, with some evidence of scour and streambank erosion present (Appendix H).
- Above I-5, the creek is generally broad and relatively unconfined. It can best be described as a riparian wetland with a integral stream channel.
- Channel complexity is generally low throughout the Murray Creek system. Below I-5, the stream is somewhat channelized, with low sinuosity. Above I-5, the stream is essentially one long glide with low channel sinuosity. Glides are intermediate habitat units that have characteristics of both pools and riffles but provide little of the functional capabilities of either. Although relatively deep and slow during baseflow conditions like pools, glides provide little refuge during peak-flows. Glides are also usually slow water habitat where finer sediment predominate, making them poor spawning habitat. The wetland nature of much of upper Murray Creek makes this glide-dominance not as big a problem as it would be on typically lowland streams.
- The lower Sequalitchew Creek channel is a typical low-gradient, meandering pool-riffle channel, with good natural complexity.

Spawning Habitat

- There is adequate usable spawning habitat (riffles) in the survey reaches of Murray Creek (Appendix H). There were several patches of suitable spawning gravels noted within the wetland segment of upper Murray Creek, including just below Kinsey Marsh in the headwaters. In that the primary salmonid species found in the creek is cutthroat, there appears to be generally good spawning opportunities.
- RQI scores indicate the quality of spawning habitat in each riffle. High quality riffles have clean substrate, low embeddedness, and abundant cover. Mean RQI scores on the Murray Creek segments were good (Appendix H).
- Spawning habitat in lower Sequalitchew Creek is generally good, both in quality (RQI = 3.5) and quantity (52% riffles), although the streambed is highly embedded with fine sediment in several places (Appendix H).

Rearing Habitat

- There is a lack of pool habitat in the lower segment (below I-5) of Murray Creek (Appendix H). Rearing habitat is generally poor in this reach. This is primarily due to the lack of LWD.
- There is adequate, usable rearing habitat (pools) in the upper reaches of Murray Creek (Appendix H). This is primarily due to the presence of wetland glides, as well period pools formed by LWD.

- PQI scores indicate the quality of rearing habitat in each pool. High quality pools are generally deep, large in size, and have abundant cover. Mean PQI scores on lower Murray Creek is poor. The PQI scores for upper Murray Creek were generally good (Appendix H). The NMFS MPI suggests 30 pools/km indicate properly functioning conditions. None of the Murray Creek reaches achieved this goal.
- Rearing habitat in lower Sequalitchew Creek is adequate, both in quality (PQI = 2.5) and quantity (35% pools), although the residual pool depth is very shallow (Appendix H).

Habitat Quality Index (HQI)

- The habitat quality of the assessed segments of Murray Creek was evaluated using the HQI. The summed score of eight metrics determined the final HQI score (see Results for details). The lower Murray Creek HQI score was in the poor habitat quality category (mean score = 14 out of a possible 50). The upper Murray Creek HQI score was fair (mean score = 24 out of a possible 50) indicating that habitat conditions could be significantly improved with better management and targeted restoration projects (Appendix H).
- The HQI score for lower Sequalitchew Creek was good (mean score = 37 out of a possible 50).

Biological Integrity

- Murray Creek on Fort Lewis had a B-IBI score of 20 (out of a possible 50) and is rated as poor.
- Sequalitchew Creek had a B-IBI score of 24 (out of a possible 50) and is rated as poor.
- Cutthroat trout were the only salmonids noted in Murray Creek on Fort Lewis during project field surveys.

Chemical Water Quality

This study did not specifically assess chemical water quality.

Photographs

See Appendix L for pictures of Murray and Sequalitchew Creeks on Fort Lewis.

Recommendations

1. Salmonid habitat in Murray Creek is generally functional, although it is degraded throughout the watershed due to the cumulative impacts of human land-use activities (*Fort Lewis*, 1996). The stream-riparian corridor is encroached by surrounding development, especially in the lower and middle reaches and has little of its natural habitat complexity and diversity. In spite of this, there is excellent opportunity to improve instream habitat conditions within the Fort Lewis segments, especially in the middle and upper sub-basins. Some potential habitat enhancement projects include:
    - Pool creation using LWD
    - General LWD enhancement

- Spawning gravel addition
- Streambank re-vegetation
- Exotic vegetation removal

2. The riparian corridor of Murray Creek on Fort Lewis, and especially Camp Murray, can be significantly improved by removal of exotic vegetation, lawn, and landscaped areas. These areas should be re-vegetated with native trees, shrubs, and groundcover. In addition, the buffer width in each segment of the stream should be maximized, with consideration given to the relocation of parking lots or other non-essential infrastructure. The goal should be to increase canopy cover, reduce the effects of development encroachment, and improve LWD recruitment potential over the long term. The lower segments on Camp Murray property are particularly in need of riparian rehabilitation. Fort Lewis has undertaken several riparian and instream habitat enhancement projects in middle and upper Murray Creek. These efforts should continue. In addition, consideration should also be given to the reintroduction of beaver into the middle reaches and headwaters of Murray Creek (Kinsey Marsh).
3. The lower-most reach of Murray Creek, within the Camp Murray area, should be targeted for stream channel naturalization and streambank revegetation. In addition, the instream log weirs installed in this segment of the creek should be removed and a more natural LWD installation accomplished. A natural, meandering pool-riffle morphology should be the ultimate goal. Because of the importance of this segment of the stream for salmonid spawning, this should be a high priority.
4. Water quality should be a significant cause for concern on Fort Lewis. With the close proximity of vehicle maintenance operations and other potentially hazardous activities in the vicinity of Murray Creek, especially at the Logistic Center and Camp Murray areas, pollution prevention must be a high priority. The use of stormwater BMPs for all impervious surfaces is strongly advised. Specifically, structural BMPs such as sand filters and media filtration devices should be installed at all stormwater "hot-spots" (i.e., vehicle maintenance facilities, motor-pools) locations. Because of the sensitive nature of the Murray Creek groundwater recharge area (*Fort Lewis*, 1996), the use of biofiltration, infiltration, and bioretention is strongly recommended.
5. The main issue with Sequalitchew Creek is the disconnection of the headwaters from the middle and lower reaches of the creek. The diversion structure, lake management operations, and the modification of the headwater wetlands (Hunter and Edmond marshes), both on base and within the Dupont area, have all contributed to the problems in the creek downstream of Fort Lewis. The fragmentation and hydrologic alteration of the wetlands downstream of the base are probably the most significant problems affecting Sequalitchew Creek. It is recommended that the base and local jurisdictions work cooperatively to restore natural hydrologic and ecological function to the upper watershed. An integrated water management plan is needed as well as extensive wetland restoration to restore hydrologic continuity to the middle and low sections of the creek.

MILITARY INSTALLATION DATA SUMMARY
NAVAL SUBMARINE BASE BANGOR: DEVILS HOLE AND CATTAIL CREEKS

Naval Submarine Base (NSB) Bangor is located on the Kitsap Peninsula in the Puget Sound region of western Washington (Figure 32). NSB Bangor consists of a total of 7,200 acres. Hood Canal, a marine fjord of Puget Sound, borders 4.5 miles of the facility to the west. The upland area surrounding the base supports suburban and rural land uses. The landscape of the base is characterized by flat-topped ridges ranging in elevation from 300 to 500 feet, sloping down to sea level to the west along Hood Canal. Surface water drainage consists of six streams draining to Hood Canal, including two major perennial creeks (Devils Hole and Cattail) that support native salmonid populations. In addition, there are two tributary streams of Clear Creek, another salmon-producing stream, that flow off the base to the east and into Puget Sound (Figure 33). The Natural Resources Management Plan describes an integrated approach to enhance and conserve 5,500 acres of habitat on the base. The Natural Resource Program is essential to the mission and is integrated into most of base activities. NSB Bangor obtains its water from the sea level aquifer at well depths ranging from 300 to 500 feet below the ground surface. Precipitation is the primary source for replenishing the water to the aquifer system.

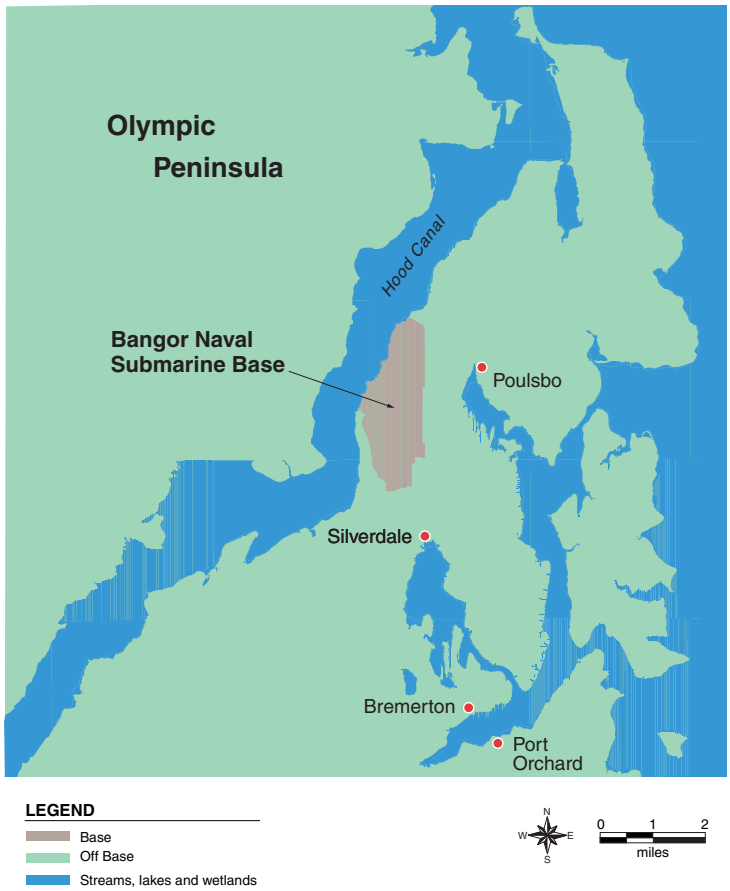

Figure 32. *Naval Submarine Base Bangor location map*

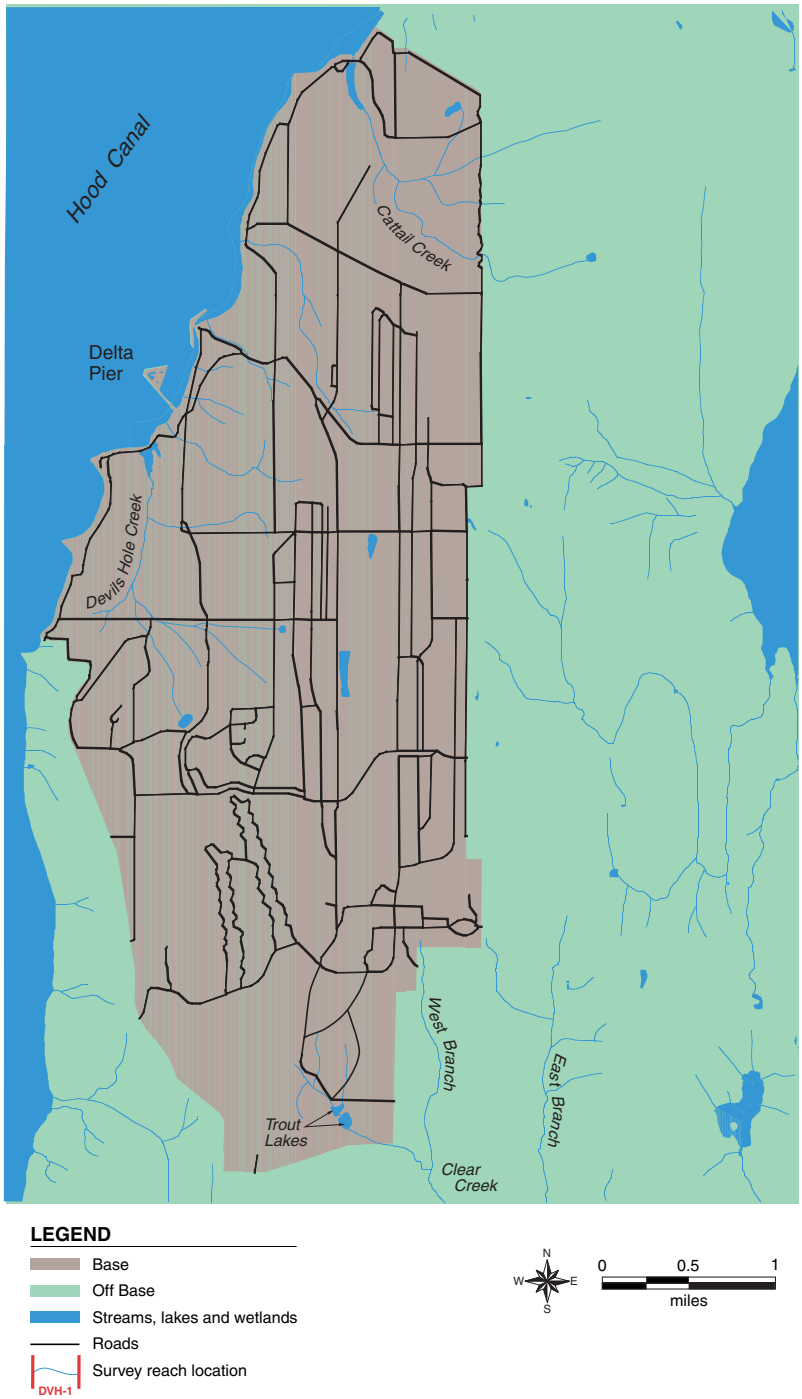

Figure 33. *Naval Submarine Base Bangor*

The primary mission of the NSB Bangor is to provide support to the Trident submarine launched ballistic missile system; to maintain and operate facilities for administration and personnel including base security, berthing, messing, environmental and recreational services; and provide logistics support to other facilities in the area. NSB Bangor hosts 54 tenant commands, most of which directly support the operational forces.

The base has an existing Stormwater Pollution Prevention Plan (SWPPP) that was completed in 1996 (*NSB Bangor*, 1996). This plan is in compliance with the 1972 Clean Water Act (CWA) and the 1987 Water Quality Act (WQA). These laws established a framework for regulating the discharge of municipal and industrial stormwater under the National Pollutant Discharge Elimination System (NPDES) permit program as administered by the US EPA. The SWPPP identifies existing and potential sources of pollutants, primarily associated with industrial activities on the base, that may reasonably be expected to affect the quality of stormwater discharges; defines selected BMPs that are designed to minimize pollutant levels in NPS discharges; and establishes a time line for implementing the plan and monitoring the effectiveness of the recommended measures. The SWPPP addresses the requirements of the NPDES program for industrial (non-construction) and construction-related activities, but may not be in full compliance with NPDES Phase II requirements that are being finalized at this time. As part of the SWPPP development, all industrial facilities on the base were inspected, potential contaminants were identified, and stormwater samples were collected. Nineteen illicit connections of non-stormwater discharges to the stormwater network were identified and corrected. As part of the SWPPP, a phased prioritized plan to construct new mitigation facilities is currently under way. In addition, an inspection program for BMP facilities and an approved stormwater monitoring plan are also outlined in the SWPPP. The SWPPP will need to be updated in the near future as NPDES Phase II regulations become active.

Stormwater treatment facilities include natural conveyances (streams and wetlands) and constructed conveyances (swales, ditches, and culverts), as well as retention and detention facilities. Most stormwater run-off is infiltrated and/or treated by engineered facilities prior to entering the natural surface-drainage network. All stormwater is treated prior to leaving NSB Bangor boundaries. Stormwater treatment ponds provide for sedimentation and limited removal of NPS pollutants. Each R/D facility includes an oil/water separator at the inlet of the pond. The main stormwater treatment ponds are

- Trident Lakes Retention Ponds (Clear Creek)
- Industrial Area Retention Pond (Clear Creek)
- Delta Pier Retention Pond (Hood Canal)
- Marginal/Service Pier Retention Pond (Hood Canal)
- Explosive Handling Wharf Retention Pond (Hood Canal)
- SWFPAC Retention Ponds (Devils Hole Creek).

Because the base is located on the sensitive and relatively pristine waters of Hood Canal, hazardous waste reduction and cleanup have been a priority. The history of the base as a major weapon-storage facility has generated several hazardous waste sites. These sites are currently being or have undergone remediation. The base also has an active oil spill prevention and control plan, including an emergency response team for both hazardous materials and oil spills. The NSB Public Works Department administers the NSB Bangor stormwater management program, although each command or facility on the base is responsible for compliance with stormwater and NPS pollution control requirements.

U.S. Navy environmental regulations and policies are stipulated in the Department of the Navy Environmental and Natural Resources Program manual (OPNAVINST 5090.1B). These regulations state that *Navy facilities must comply with all requirements of the CWA and must meet all applicable federal, state, and local stormwater permit requirements*. The use of the best available technology for reducing pollution is also stipulated.

Stream Descriptions

Cattail Creek

The Cattail Creek watershed (Figure 34) encompasses most of the sparsely developed northern portion of the base. This creek is a good example of a typical Hood Canal small-stream sub-basin. The headwaters of the creek are located outside the boundaries of the base in a relatively low-gradient area, which was probably once dominated by wetlands but is now undergoing residential development (Vinland area). For much of its length, the stream flows within a steep-walled ravine. Cattail Creek is a forced pool-riffle type of stream. LWD provides the main structural component of these types of streams and is responsible for the instream habitat complexity that is critical to maintaining a natural salmonid community and a high level of ecological integrity. The creek drains into an artificial lake (Cattail Lake), which flows directly into Hood Canal via two level-control structures. This outlet has no fish-way installed on the outlet of Cattail Lake and therefore this has effectively blocked all anadromous salmonid migration upstream. The lake is stocked with trout for recreational fishing.

Cattail Creek is the least developed sub-basin within the base. Its stream system is relatively unaffected by human activities and has high overall ecological integrity. The stream has the potential to support salmonid populations, both resident and anadromous. The *Washington Department of Fish and Wildlife Stream Catalog* (*WDFW*, 1975) lists Cattail Creek as historically supporting coho, chum, and cutthroat. Cattail Lake, the wetland area around its inlet, and the mainstem of the stream itself have diverse and complex instream habitat. There is adequate spawning and rearing habitat within the stream system to support native salmonids. The quality of the riparian zone is generally good to excellent. The major salmonid-related problem for this watershed is the lack of a fish-way (fish ladder) at the outlet of Cattail Lake on Hood Canal. Any historical runs of coho or chum salmon have been extirpated due primarily to this migration barrier.

This watershed is distinguished in that its headwaters are predominantly located outside the jurisdiction of NSB Bangor. The headwaters of the north and south tributaries are entirely outside the base. The smaller, middle tributary also begins just outside the base boundary. This results in a difficult watershed management issue. The headwaters of this creek are located in an area of northern Kitsap County that is undergoing a significant amount of residential development. The headwaters of the north, south, and middle tributaries are located in the Vinland area, which is predominantly zoned as low-density residential. To minimize impact on the downstream portion of Cattail Creek, the headwaters should be protected, and any development in these areas should include stormwater mitigation measures. Headwater wetlands and the stream's riparian corridor should be preserved. This will require NSB Bangor to work closely with Kitsap County to minimize the impacts of future upland development on the stream channel. This is a relatively confined, moderate-gradient stream with the potential for erosion of the stream bank and incision of the streambed if flows increase in magnitude and frequency owing to upstream development.

The mainstem of Cattail Creek is generally in a natural condition. There are several mass-wasting (landslide) sites along the side slopes of this creek, but this is typical of the highly confined stream channels that drain into Hood Canal. However, it should be noted that these types of stream channels can be highly susceptible to development pressure along the upland areas bordering on the incised valleys. Wide riparian buffers are

recommended to reduce the chance of excessive mass-wasting due to run-off from developed areas.

Overall, there is a low level of instream structure (LWD), and salmonid habitat is generally of adequate quality. LWD recruitment potential is generally good throughout the mainstem segment. The riparian corridor is predominantly mature coniferous forest. The lowest reach of the mainstem, prior to flowing into Cattail Lake, is composed of a high-quality wetland area that would provide excellent coho rearing habitat. The middle and upper reaches of the mainstem have excellent spawning habitat and adequate rearing habitat. It is likely that this area was a typical small-stream estuary prior to the construction of the road and lake. Other similar streams along the Hood Canal typically have a brackish wetland at the mouth of the creek and a tidally influenced estuary.

The north, middle, and south tributaries are less confined than the mainstem but generally have a higher gradient (2–4%). There is adequate instream structure (LWD), and the quantity and quality of salmonid habitat are for the most part good. All three tributaries pass under the NSB Bangor boundary road. These locations are the only stream crossings that exist within the watershed. This is on one hand excellent, but it also presents a problem. The culvert under the north tributary road is perched and therefore is a barrier to fish passage. However, little usable habitat exists upstream of the base on this tributary owing to past development in the Vinland area. The current culvert is undersized based on present and future development upstream. There is no culvert under the NSB-Bangor boundary road on the middle tributary. While this tributary is currently neither a salmonid passage nor a flow problem owing to the ephemeral nature of the stream, future development upstream has the potential to wash out the boundary road during periods of high run-off. New, larger-diameter culverts are recommended for both the north and middle tributaries to alleviate these potential problems.

The south tributary has already experienced high storm flows that resulted in a near washout of the existing bridge during the winter of 1996–1997. The configuration of the boundary road and the routing of road run-off were at least partially responsible for the severe mass-wasting that occurred along this section of the channel. The stream channel must be rehabilitated (LWD installed) and the valley slopes re-vegetated. In addition, the run-off from the boundary road should be routed through a stormwater-treatment facility and not allowed to run directly into the stream. The upstream segment of the south tributary has the most potential for salmonid utilization in the Cattail Creek headwaters.

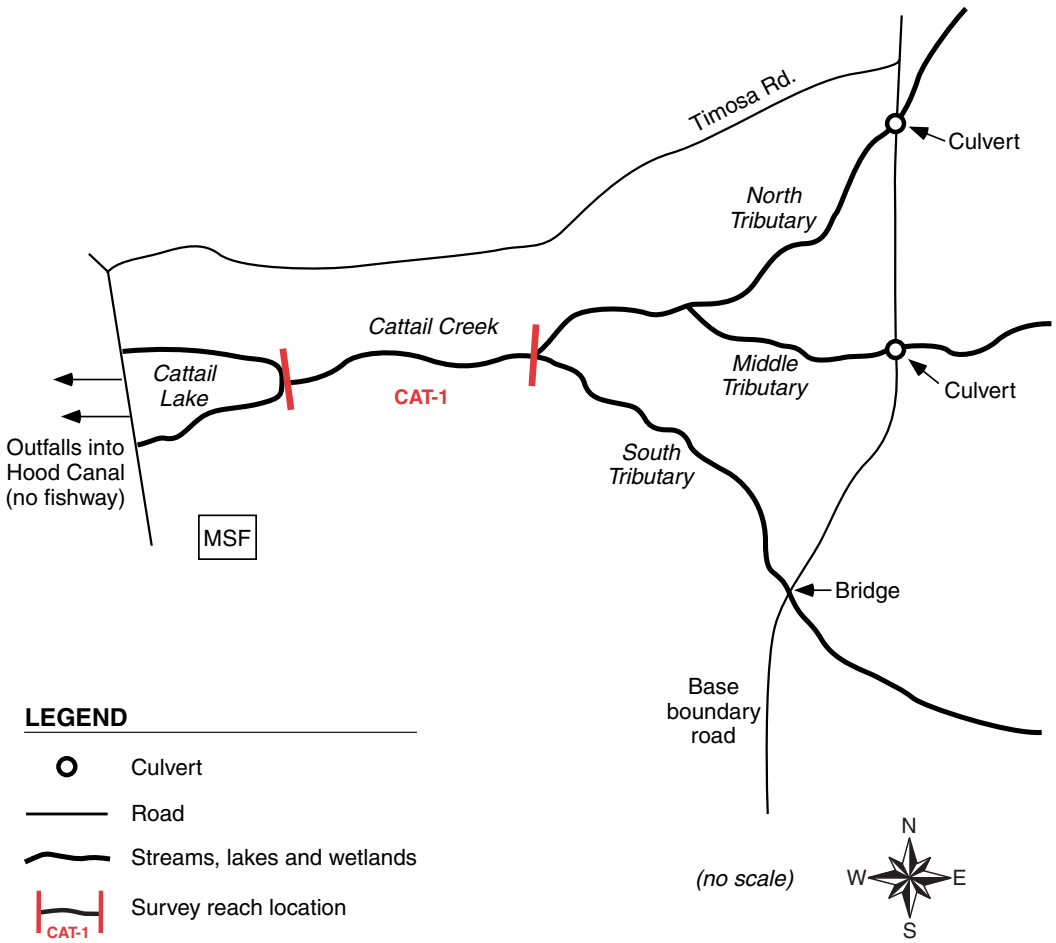

Figure 34. *Cattail Creek sub-basin on NSB Bangor*

Devils Hole Creek

Devils Hole Creek (Figure 35) is the largest of the Hood Canal streams on NSB Bangor. The headwaters of this creek are almost entirely within the restricted boundaries of the Strategic Weapons Facility Pacific (SWFPAC), which consists mainly of open (grass-covered) land, roads, and weapon-storage buildings. The creek also flows through the Trident refit facility (TRF) industrial area before entering Devils Hole Lake. While the headwaters have been affected by development, the segment of the creek between TRF and Devils Hole Lake is relatively undisturbed. This man-made lake drains directly into Hood Canal via a fish ladder, which affords access to the creek for anadromous salmonids.

Devils Hole Creek drains the west-central portion of NSB Bangor. The headwaters of the creek include the western section of SWFPAC and the Escolar Road corridor (Figure 35). The basin contains several industrial areas, the TRF being the most notable. Several roads and parking lots are also situated in the upper and middle sub-basins. The lower portion of the creek is relatively unimpacted until it enters Devils Hole Lake prior to draining into Hood Canal. Devils Hole Lake is a man-made impoundment that was created when the perimeter road was installed along Hood Canal. This lake area was likely a typical small stream estuary prior to the road being built. The wetland around the stream mouth

provides high quality rearing habitat. A fish ladder has been installed at the lake outlet to allow migration of anadromous fish. Coho and chum salmon, as well as cutthroat trout, currently utilize the stream system. The entire stream basin is located within NSB Bangor.

Devils Hole Lake, the wetland area around its inlet, and the mainstem of the stream itself has a diverse and complex instream salmonid habitat. There is adequate spawning and rearing habitat within the stream system. The quality of the riparian zone is generally good. Devils Hole Creek is a relatively confined, moderate-gradient stream with the potential for stream-bank erosion and streambed incision if flows increase in magnitude and frequency owing to upstream development. The lower mainstem is in a natural condition. There are several mass-wasting sites along the side slopes of this creek, but this is typical of the highly confined stream channels that drain to Hood Canal. The mainstem has adequate instream structure (LWD), and salmonid habitat is generally of high quality. LWD recruitment potential is generally good throughout this segment. The riparian corridor is predominantly mature coniferous and mixed forest. The middle and upper reaches of the mainstem have good spawning habitat and adequate rearing habitat. There appears to be more fine sediment than would be expected in a completely natural stream. This may be due to human activities upstream.

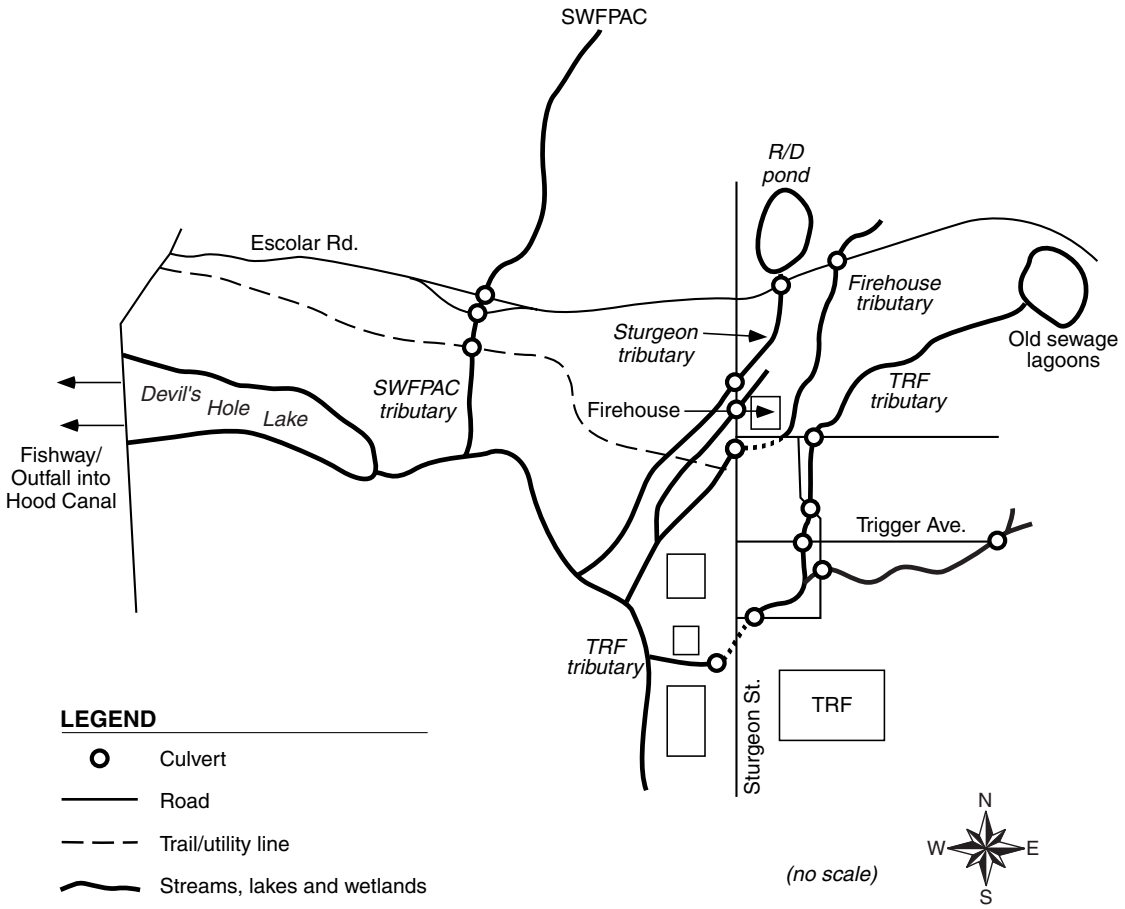

Figure 35. *Devils Hole Creek on NSB Bangor*

The lowest tributary of the creek enters from the north near the head of the lake-wetland area. The headwaters of this tributary include a portion of SWFPAC that consists of open fields, roads, and forest. This upper section of the tributary is strongly affected by development (SWFPAC) and is somewhat degraded. The tributary is seasonal upstream of Escolar Road. The SWFPAC tributary flows through two culverts under Escolar Road and an access road. The creek then flows through a culvert under a combination utility access road and jogging trail (an old RR grade). This culvert is also perched, forming a fish passage barrier, and is undersized for existing storm-flow conditions. On the upstream side of the utility-line crossing, a run-off channel enters from the east. Surface erosion and incision is evident here. Downstream of this crossing, the SWFPAC tributary flows through a naturally forested, fairly deep ravine before joining with the mainstem of Devils Hole Creek. The channel is quite steep and has the potential for incision and stream-bank erosion. There are dense blackberries covering this tributary channel just below the jogging trail. The lower segment of this tributary is a pool-riffle type stream, which supports native salmonids.

Another right-bank tributary has its headwaters within SWFPAC and drains into a two-cell stormwater-treatment facility (constructed wetland) on the upstream side of Escolar Road. The overflow from this pond goes through a culvert under Escolar Road and into the tributary. Road run-off from Sturgeon Street also flows into this tributary. Several reaches of the tributary are choked by dense blackberry growth and the tributary riparian zone is lacking in conifers for much of its length. This tributary also flows under the utility road and jogging trail before joining the mainstem. The lower segment of this tributary is almost entirely riffles and has extensive streambank erosion present.

The mainstem of Devils Hole Creek splits into two main tributaries in a low-gradient area behind the Sub-Mart and SWSMS complex (Buildings 7001/7002/7003). One tributary runs through the TRF complex before branching into two small ephemeral channels, while the other runs past the TRF firehouse in two small perennial branches. The headwaters for both these tributaries include a good portion of SWFPAC to the east of Escolar Road. Both branches flow through areas of second-growth, mixed forest and riparian wetlands. Both have good spawning and rearing habitat for coho salmon and cutthroat trout. The lowermost portions (downstream of Sturgeon Avenue) are in good condition, with complex instream salmonid habitat. The middle portions (upstream of Sturgeon Avenue) have been significantly degraded by human activity in and around the TRF industrial complex. The upper, headwater portions are generally in good condition.

The west branch of the "firehouse" tributary has its headwaters within SWFPAC on the upstream side of Escolar Road. The east fork flows through a forested section into the firehouse pond (which also serves as a children's fishing pond) and then under Sturgeon Avenue, where it joins the main firehouse tributary. This tributary has generally good instream quality. This sub-basin is mainly forested (mixed mature) and is in generally good condition. The upper segment of the firehouse tributary has pockets of good spawning and rearing habitat, as well as adequate instream structure and complexity (LWD). The section of the branch around the firehouse is moderately affected by development pressure, including dense blackberry growth in patches as well as other exotic vegetation. The area behind the firehouse was cleared within the past 5–10 years and has grown back with predominantly brush and alders. The riparian corridor near the firehouse is in need of enhancement. As a result of the loss of riparian forest and increased storm flows, there is a lack of instream LWD, and stream-bank erosion is

common over the entire reach. Instream LWD installation and bank stabilization is recommended. The firehouse tributary flows under Sturgeon Avenue and the jogging trail before joining the mainstem of Devils Hole Creek. The long culvert under Sturgeon Street is undersized for current and future flow conditions and is a barrier to salmonid migration. This culvert should be replaced with an arched culvert to facilitate fish passage as well as accommodate storm flows. The culvert's outlet on the west side of Sturgeon Street is currently buried under a layer of sediment.

The TRF tributary has its headwaters in SWFPAC, along Escolar Road, and in two former sewage ponds located at the corner of Golet Road and Escolar Road. The tributary flows through a low-to-moderate gradient, forested area, which is predominantly riparian wetland. The stream channel is not well defined in this area. This section has good spawning and rearing habitat for coho and cutthroat. Both species have been known to utilize this tributary. The stream flows through a culvert under Snook Road, then alongside a parking lot, through another culvert under an access road, through a ditched section, and under Trigger Avenue via a very long culvert. This is a tortuous path for salmonids to migrate, with little usable spawning or rearing habitat upstream.

Downstream of the Trigger Avenue crossing, the stream is channelized through a wooded area adjacent to the TRF complex. This area between Trigger Street and TRF has natural wetland characteristics but is of poor quality owing to stormwater run-off and encroachment by human activity. The salmonid habitat is also poor, with almost no instream LWD, excessive deposition of fine sediment in spawning gravels, and little rearing habitat (pools). The culvert under Sturgeon Street is also problematic from a flow-capacity and fish-passage point of view.

Devils Hole and Cattail Creek Data Analysis

Watershed Characterization

NSB Bangor comprises over 7,000 acres, over 50% of which are undeveloped, natural forested areas, and includes three perennial small-stream watersheds (Figure 33). The base also includes several seasonal small-stream watersheds, a majority of which drain into Hood Canal. One of these perennial watersheds, Devils Hole Creek, is entirely within NSB Bangor. Another, Cattail Creek, has its headwaters located off base, with the majority of the watershed contained within the base boundaries. Both of these creeks flow generally from east to west into Hood Canal. The third major stream draining the base, Clear Creek, flows to the southeast into Puget Sound. The headwaters of two tributaries of Clear Creek are located within NSB Bangor. These three situations illustrate the most common scenarios with respect to the relationship between watersheds and base jurisdictional boundaries. Each of these streams present unique challenges for DoD natural resource management.

Land-use within NSB Bangor is a mixture of military operational, administrative, residential, industrial, and commercial land uses. NSB has an extensive amount of native forest land cover, especially in the sub-basins draining to Hood Canal. Most of the developed areas on base are located within the Clear Creek sub-basin on the east side of the base (Figure 32). The Devils Hole watershed has most of its development clustered in the central part of the sub-basin around the TRF complex. The large areas of open area

within the SWFPAC complex at the headwaters also contribute to the overall level of imperviousness. Cattail Creek watershed is mostly forested, with very little development (Table 22).

Table 22. *Land-use and land-cover data for NSB Bangor (%)*

Watershed	**Total Impervious**	**Native Forest**	**Native Grass**	**Bare Soil**	**Urban Forest**	**Urban Grass**	**Urban Paved**
NSB BANGOR							
Devils Hole Creek	**27**	54.8	6.5	0.3	11.5	19.8	7.1
Cattail Creek	**11**	78.0	5.4	0.0	12.0	4.5	0.1

Basin Land-use

- Table 22 summarizes the land-cover and land-use data for the Devils Hole and Cattail Creek watersheds. NSB Bangor, as a whole, is approximately 30% impervious, including the roads, parking areas, buildings, and landscaped areas. Buildings, parking lots, and landscaped areas dominate the developed portions of the base.
- Road density within NSB Bangor is only 3.0 km/km^2 total. The road density in Cattail Creek watershed is only 0.78 km/km^2 and only 1.1 km/km^2 in the area contributing to Devils Hole Creek. Generally, a road density over 3 km/km^2 is considered high and is expected to have a significant impact on aquatic resources (*May et al*., 1997).
- Relatively large areas of native wetland and forest still exist on the base. These areas contain a diverse array of native flora and fauna, including some endangered species.

Riparian Corridor Continuity

- DVH-1: The riparian corridor is intact, with no fragmentation.
- DVH-2: The riparian corridor is intact, with no fragmentation.
- DVH-3: The riparian corridor is relatively intact, with minimal fragmentation (two road crossings).
- DVH-4: The riparian corridor is relatively intact, with minimal fragmentation (two road crossings).
- DVH-5: The riparian corridor is intact, with no fragmentation.
- CAT-1: The riparian corridor is intact, with no fragmentation.

Riparian Integrity

- DVH-1: The riparian forest is a mixture of mature conifers and deciduous trees with a well-established understory and groundcover layers. The riparian zone is wide and intact. LWD recruitment potential is rated as good to excellent. Riparian integrity is high for this segment.
- DVH-2: The riparian forest is a mixture of mature conifers and deciduous trees with a well-established understory and groundcover layers. The riparian zone is wide and intact. LWD recruitment potential is rated as good to excellent. Riparian integrity is high for this segment.
- DVH-3: The riparian forest is predominately mixed forest (both mature and young). The riparian zone is wide and intact. LWD recruitment potential is rated as fair to good. Invasive and exotic species (blackberries, reed canary grass, etc.) are present in patches, especially around road crossings. Riparian integrity is moderate for this segment.
- DVH-4: The riparian forest is a mixture of mature conifers and deciduous trees with a well-established understory and groundcover layers. The riparian zone is wide and intact except through the TRF complex reach. LWD recruitment potential is rated as good to excellent. Riparian integrity is high for this segment.
- DVH-5: The riparian forest is predominately mixed forest (both mature and young). The riparian zone is wide and intact. LWD recruitment potential is rated as fair to good. Invasive and exotic species (blackberries, reed canary grass, etc.) are present in patches, especially around road crossings. Riparian integrity is moderate for this segment.
- CAT-1: The riparian forest is a mixture of mature conifers and deciduous trees with a well-established understory and groundcover layers. The riparian zone is wide and intact. LWD recruitment potential is rated as good to excellent. Riparian integrity is high for this segment.

Canopy Cover

- DVH-1: The riparian zone is dominated by mixed-mature forest and the canopy cover is relatively closed in this reach.
- DVH-2: The riparian zone is dominated by mixed-mature forest and the canopy cover is relatively closed in this reach.
- DVH-3: The riparian zone is dominated by mixed-mature forest and the canopy cover is relatively closed in this reach.
- DVH-4: The riparian zone is dominated by mixed-mature forest and the canopy cover is relatively closed in this reach.
- DVH-5: The riparian zone is dominated by mixed-mature forest and the canopy cover is relatively closed in this reach.

- CAT-1: The riparian zone is dominated by mixed-mature forest and the canopy cover is relatively closed in this reach.

Large Woody Debris

LWD is a key structural feature in PNW streams. LWD is the main pool-forming element in lowland streams and is responsible for much of the natural channel complexity in these streams (*Maser et al*., 1988). The desired frequency of LWD for PFC is > 400/km, with < 200/km considered inadequate. This equates to a normalized target BFW-spacing of 2 pieces of LWD per BFW-length of stream channel (*Peterson et al*., 1992). Large, key pieces of LWD are especially important because they are relatively stable and provide long-term habitat as well as instream cover for salmonids. The PFC target for key LWD is generally considered to be > 50/km or about 25% of the total LWD.

- DVH-1: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. However, on a more positive note 25% of the LWD was classified as key and 90% of the LWD was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The lack of adequate instream LWD is the most significant deficiency in this segment.
- DVH-2: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. However, on a more positive note 30% of the LWD was classified as key and 80% of the LWD was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The lack of adequate instream LWD is the most significant deficiency in this segment.
- DVH-3: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. However, on a more positive note 30% of the LWD was classified as key and 75% of the LWD was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The lack of adequate instream LWD is the most significant deficiency in this segment.
- DVH-4: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. However, on a more positive note 25% of the LWD was classified as key and 65% of the LWD was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The lack of adequate instream LWD is the most significant deficiency in this segment.

- DVH-5: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. In addition, only 15% of the LWD was classified as key and 50% of the LWD was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The lack of adequate instream LWD is the most significant deficiency in this segment.
- CAT-1: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. However, on a more positive note 35% of the LWD was classified as key and 90% of the LWD was coniferous. Channel complexity was generally low in this segment, as was LWD recruitment potential. The lack of adequate instream LWD is the most significant deficiency in this segment.

Rearing Habitat

Adequate high-quality rearing habitat (pools) is generally recognized as one of the critical factors limiting salmonid productivity. This is especially true of winter rearing habitat for juvenile coho salmon (*Brown and McMahon*, 1987; *Reeves et al*., 1989; *Nickelson et al*., 1992). LWD is probably the key component of salmonid rearing habitat in small streams in the PNW and is critical to over-winter survival of juvenile coho salmon (*Bustard and Narver*, 1975; *Brown and McMahon*, 1987; *McMahon and Hartman*, 1989; *Nickelson et al*., 1992). LWD not only provides habitat structure, complexity, and a high-flow refuge but is a major form of instream cover for young fish. Coho, in particular, have a strong preference for pools with a structurally complex (LWD) microhabitat (*McMahon and Hartman*, 1989). Cutthroat trout appear to prefer a similar rearing habitat, but may be more adaptable to less than ideal conditions (*Heggenes et al*., 1991). Watershed land use (development) has reduced the quantity of rearing habitat (pools) and degraded pool quality as well (*Meehan*, 1991). The pervasive and long-term nature of urbanization has been especially hard on instream habitat in general and on rearing habitat in particular (*Booth and Reinelt*, 1993). The PSL stream study showed a significant reduction in the quantity and quality of rearing habitat due to the cumulative effects of watershed development (*May*, 1996).

Rearing habitat typically mirrors the quantity and quality of LWD in the stream channel. PQI scores indicate the quality of rearing habitat in each pool. High quality pools are generally deep, large in size, and have abundant cover (LWD, overhanging vegetation, etc.). The NMFS MPI suggests 60–80 pools/km for PFC in streams with a bankfull width of 5–10 m. Pool BFW-spacing should be less than 2 (*Peterson et al*., 1992). In addition, the % pool habitat (by surface area) should be 40–60% for low gradient streams, such as the lowland streams in this study. RPD should be relatively deep to provide good cover and temperature refugia.

- DVH-1: Pool frequency, pool BFW-spacing, and the % pool habitat (22%) were all well below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally good (PQI = 3.0).
- DVH-2: Pool frequency, pool BFW-spacing, and the % pool habitat (16%) were all well below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally good (PQI = 3.0).
- DVH-3: Pool frequency, pool BFW-spacing, and the % pool habitat (13%) were all well below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally good (PQI = 3.0).
- DVH-4: Pool frequency, pool BFW-spacing, and the % pool habitat (18%) were all well below the MPI-target range. In addition, average RPD was relatively shallow. The quality of pools in this segment was generally fair (PQI = 2.0).
- DVH-5: Pool frequency, pool BFW-spacing, and the % pool habitat (19%) were all well below the MPI-target range. In addition, average RPD was relatively shallow. The quality of pools in this segment was generally fair (PQI = 2.0).
- CAT-1: Pool frequency, pool BFW-spacing, and the % pool habitat (23%) were all below the MPI-target range. In addition, average RPD was relatively shallow. However, the quality of pools in this segment was generally good (PQI = 3.0).

Spawning Habitat

RQI scores indicate the quality of spawning habitat in each riffle. High quality riffles have clean substrate, low embeddedness, and abundant instream cover. In addition, the % riffle habitat (by surface area) should be 40–50% for low gradient streams, such as these lowland streams. In general, the quantity of salmonid spawning habitat (riffles and pools) in NSB Bangor streams appears to be adequate. For low-gradient (< 4%), pool/riffle streams like those found in the PSL region, spawning (riffle) habitat should comprise about 40–60% of the wetted surface area of the stream (*Peterson et al*., 1992). For the streams located within NSB Bangor, all sections of Devils Hole Creek are 40–60% riffles.

In addition to the quantity of spawning habitat, the quality of existing habitat is also important. The process of spawning site selection by female salmonids is not well understood (*Groot and Margolis*, 1991). However, there is a combination of factors that determine acceptability for most species. These include the size distribution of substrata particles, water depth, water velocity, gravel permeability (fine sediment content), streambed topography, and protective cover during the spawning process. The exact characteristics of acceptable spawning sites will depend on the species, the size of the female, and the number of acceptable sites available. Within the range of sites where spawning habitat is acceptable, female salmonids appear to apply a second set of criteria

to select the optimum site for redd construction. The basis of this site selection is believed to be intragravel flow conditions favorable for incubation and development of embryos (*Crisp and Carling*, 1989). Suitable intragravel flow conditions occur where the infusion of oxygenated surface water into the streambed is enhanced by a combination of bed topography, instream hydraulic conditions, and gravel permeability. Pool tail-outs are most often identified as the optimum sites for redd construction because of the natural down-welling flow common to these areas.

Land-use activities such as timber harvesting, mining, grazing, and urban development can have a significant negative impact on spawning habitat, as can catastrophic natural events (e.g., floods or debris flows). Besides scouring and destruction of spawning areas due to high flows, probably the most damaging effect of human activity is the deposition of excessive fine sediment in spawning gravels (*Chapman*, 1988). To some extent, female salmonids have the ability to modify the streambed to improve the quality of spawning habitat by winnowing fine sediment from the redd during its construction. However, deposition of sediment after redd construction can significantly degrade the quality of the incubating environment. Excessive fine sediment has been associated with reduced survival to emergence of salmonids because of reduced intragravel water flow (*Chapman*, 1988).

In general, excessive fine sediment was noted in most of the stream segments surveyed at NSB Bangor. This sediment appears to be coming from two related sources. One is internal to the stream channel, erosion of stream banks due to the combination of high storm flows and the lack of LWD. The other is external to the stream channel, deposition of sediment in the stream by urban stormwater run-off. Correcting this problem will require both rehabilitation of instream habitat and construction of stormwater treatment facilities.

- DVH-1: Spawning habitat quantity (60%) and quality (RQI = 3.0) were both within the PFC range in this survey segment.
- DVH-2: Spawning habitat quantity (59%) and quality (RQI = 3.0) were both within the PFC range in this survey segment.
- DVH-3: Spawning habitat quantity (49%) and quality (RQI = 3.0) were both within the PFC range in this survey segment.
- DVH-4: Spawning habitat quantity (53%) and quality (RQI = 3.0) were both within the PFC range in this survey segment.
- DVH-5: Spawning habitat quantity (52%) and quality (RQI = 3.0) were both within the PFC range in this survey segment.
- CAT-1: Spawning habitat quantity (52%) and quality (RQI = 3.5) were both within the PFC range in this survey segment.

Habitat Quality Index (HQI)

The habitat quality of the assessed segments of Devils Hole Creek (Appendix I) and Cattail Creek (Appendix J) was evaluated using the HQI. The summed score of eight metrics determined the final HQI score (see Results for details). In addition, streambank stability was generally found to be good throughout Devils Hole and Cattail Creeks, indicating that excessive stormflows are not a major watershed problem.

- DVH-1: HQI = 39 (Good)
- DVH-2: HQI = 37 (Good)
- DVH-3: HQI = 37 (Good)
- DVH-4: HQI = 34 (Good)
- DVH-5: HQI = 37 (Good)
- CAT-1: HQI = 39 (Good)

Biological Integrity

In general, the biological integrity of streams on NSB Bangor was found to be within the natural range. In most cases, the B-IBI scores were in the "good" range (Appendices I and J). Devils Hole Creek and Cattail Creek were previously sampled for macroinvertebrates during September 1997. The results for both Devils Hole Creek and Cattail Creek were similar to the 2000 B-IBI samples, with Cattail scoring a 35 and Devils Hole a 30 (location was just upstream of the lake, which does not correspond to any of the current sample sites). Both creeks had "good" biological integrity in 1997. It is strongly recommended that a biological monitoring plan be established for NSB Bangor. This plan should utilize benthic macroinvertebrates as the indicator organisms and should utilize a multi-metric index for analysis. The B-IBI developed by *Karr* (1996) for the PNW, and used in this study, is recommended.

- DVH-1: B-IBI Score = 34 (Fair)
- DVH-2: B-IBI Score = 34 (Fair)
- DVH-3: B-IBI Score = 36 (Good)
- DVH-4: B-IBI Score = 44 (Good)
- CAT-1: B-IBI Score = 42 (Good)

Chemical Water Quality

This study did not specifically assess chemical water quality. Analysis of data taken as part of the current SWPPP indicates that chemical composition of the water is acceptable by US EPA and Washington Department of Ecology standards. The water quality data included samples from outlets of stormwater treatment facilities as well as stream outfalls (receiving waters). The stormwater and receiving-water sampling plan described in the NSB Bangor SWPPP appears to be adequate. Emphasis should be placed on sampling during storms rather than adhering to a strictly periodic sampling schedule.

NSB Bangor Stream Photographs

Middle mainstem of Cattail Creek

Beaver activity in upper Devils Hole Creek

Middle mainstem of Devils Hole Creek

Recommendations

1. Several salmonid migration barriers on NSB-Bangor streams were identified as fish-passage barriers or potential barriers under current and future flow conditions.

Culverts serve two main purposes: to provide a conveyance route under the roadbed and to allow fish passage. If designed and installed properly, a culvert can perform both tasks concurrently under a full range of flow conditions. The culvert must be sized and sited correctly to allow downstream passage of water, bedload, and debris (LWD). Upstream development subsequent to installation of a culvert can create flows (water and bedload) far in excess of the structure's design capacity and block fish passage. In the PNW fish passage includes upstream migration of anadromous and resident salmonids during the spawning season, as well as movement (upstream or downstream) of juveniles or resident adults at various times of the year (*Reeves et al*., 1989; *Heggenes et al*., 1991; *Nickelson et al*., 1992; *Peterson et al*., 1992).

A barrier to fish passage is defined as any physical feature in the stream that causes excessive delay in fish migration and/or abnormal expenditure of energy during any life stage of the fish. Barriers can be natural or artificial. In addition, they can be partial, total, or temporary in nature. The most common man-made barriers to fish passage found in the PNW are road culverts. Typical fish-passage problems associated with culverts include the following (*May*, 1997):

- An excessive drop at the culvert's outlet (so-called "perched" culverts)
- Too high a velocity at the culvert's inlet (fish unable to exit)
- Depth and/or velocity problems within the culvert during flow extremes
- Accumulation of debris at the culvert's inlet (inadequate capacity)
- Misalignment of the culvert with respect to the stream channel
- Too long a culvert (beyond the endurance of the fish)
- Culverts installed at too steep a gradient (resulting in high flows)
- Culverts with no resting pools at inlets or outlets
- Stream-bank erosion, scouring, and deposition due to poor culvert road fill

Blocking culverts in the Devils Hole Creek watershed were found to have a significant negative impact on accessibility of suitable spawning and rearing habitat to native salmonids. The impassable culverts identified here represent about one-third of all the usable salmonid spawning and rearing habitat in Devils Hole Creek. It is estimated that between 1.5 and 2.0 kilometers of habitat are blocked by these man-made barriers. All of these culverts should be replaced with bridges or bottomless, arched culverts of appropriate design. The culvert barriers on Devils Hole Creek include the following:

- The three culverts on the SWFPAC tributary of Devils Hole Creek are impassable (Figure 35). The culverts are undersized for current flow conditions and are all perched.

- The firehouse tributary culvert under Sturgeon Steet on upper Devils Hole Creek is assessed as a complete barrier to upstream salmonid migration (Figure 35). The culvert is undersized for current flow conditions and is too long. In addition, the outlet of the culvert is buried by sediment deposition.

- The sturgeon tributary culvert under the old railroad bed on upper Devils Hole Creek is assessed as a complete barrier to upstream salmonid migration (Figure 35). The culvert is undersized for current flow conditions and is too

steep. In addition, the outlet of the culvert is perched about a meter above the streambed.

- The sturgeon tributary culvert under Sturgeon Steet on upper Devils Hole Creek is assessed as a complete barrier to upstream salmonid migration (Figure 35). The culvert is undersized for current flow conditions and is too steep. In addition, the outlet of the culvert is perched about a meter above the streambed.
- The TRF tributary culvert under Sturgeon Street on upper Devils Hole Creek is assessed as a near-complete barrier to upstream salmonid migration (Figure 35). The culvert is undersized for current flow conditions and is too long.
- The TRF tributary culvert under Trigger Avenue on upper Devils Hole Creek is assessed as a near-complete barrier to upstream salmonid migration (Figure 35). The culvert is undersized for current flow conditions, is too steep, and is too long.
- The TRF tributary culvert under the access road at the TRF overflow parking lot is assessed as a complete barrier to upstream salmonid migration (Figure 35). The culvert is undersized for current flow conditions and is too steep.
- The TRF tributary culvert under Snook Road is assessed as a complete barrier to upstream salmonid migration (Figure 35). The culvert is undersized for current flow conditions and is too steep.
- The fish-way at the mouth of Devils Hole Creek (at the lake outlet to Hood Canal) is assessed as a partial barrier for coho salmon and cutthroat trout. This fish ladder is also assessed as a complete barrier to chum salmon (potential summer and fall runs).

By far the most significant obstruction to fish passage in the Cattail Creek watershed is the lack of a fish ladder at the outlet of Cattail Lake. This has eliminated any anadromous salmonid runs that existed on this creek prior to development. Correction of this deficiency should be a high priority. The culverts on upper Cattail Creek were also assessed as complete barriers to salmonid migration, but little habitat exists upstream of these culverts, making them a lower priority for corrective action.

It is strongly recommended that the Hood Canal perimeter (Sea Lion Road) roadbed for both Devils Hole and Cattail lakes be removed and replaced by a bridge or open causeway. This action should be accompanied by the restoration of the estuaries on both creeks where the current man-made lakes now exist. The morphology of both Devils Hole and Cattail Lakes suggests that these areas were once saltwater lagoons, estuarine wetlands, and/or tidal marshes. All of these habitat types are typical of natural Hood Canal small streams. The current freshwater lakes do provide some good rearing habitat for coho and cutthroat, but do not provide the transitional habitat needed by most salmonid species, especially chum salmon, as they move between the marine and freshwater environments. This lack of estuarine habitat is a significant limiting factor for both creeks.

2. Owing to its currently undeveloped condition, the Cattail Creek sub-basin should be designated as a resource conservation area. Development within this catchment should be excluded or severely limited. The watershed should be managed for resource protection, with only low levels of recreational activity allowed. Selective timber harvest in the upland sections of the catchment may be allowed but only if it is greater than 100 m (300 ft) from the stream channel, wetland areas, and steep slopes. Because the headwaters of this stream are located off base, a close coordination with Kitsap County will be required to protect the downstream portions of the creek. For example, the base could provide land for construction of a regional stormwater-treatment facility if development is planned for the headwaters.

3. The watershed management goal for Devils Hole Creek should be to halt further degradation of stream quality and to enhance ecological integrity where possible. This will require some extensive construction of stormwater treatment facilities, rehabilitation of instream habitat, and replacement of multiple culverts if the creek is to be restored to its full potential to support native salmonids. Consideration should be given to utilizing a few of the more innovative stormwater-treatment BMPs to service NPS pollutant "hot spots" and transportation-related impervious areas. In addition, impervious surfaces should be minimized and stormwater run-off should be managed to reduce streamflows during storm events. Devils Hole Creek is susceptible to streambank erosion caused by high stormflows and the resultant fine sediment deposition in spawning gravels. Numerous outfall pipes were noted throughout Devils Hole Creek. Most of these are located in the vicinity of the TRF complex and many appear to be old and no longer in use. It is recommended that all stormwater outfalls be routed to a treatment facility prior to discharge into the creek. Any "illicit" outfalls should be corrected immediately and any unused pipes should be removed.

   The lower segments of Devils Hole and Cattail creeks are in a relatively natural condition. This is very likely due to the minimal human activity that takes place in these segments based on their location within natural ravines. The riparian corridor is relatively intact, quite wide, and dominated by mature forest. There is very little streambank erosion or streambed scour, resulting in good spawning habitat throughout the lower segments of the creek. Conservation and enhancement of this refugia area should be the primary strategy for aquatic resource management within NSB Bangor. It is recommended that stewardship of lower Devils Hole and Cattail Creeks include the following:

   - Installation of a flow gage at the mouth of the creeks to monitor changes in the hydrologic regime.
   - Long-term riparian plantings of native cedar, hemlock, cottonwood, and spruce.
   - Develop and implement a short-term LWD strategy until full riparian function is achieved.
   - Conserve native forest and prairie cover throughout the watershed and minimize impervious surfaces in all developed areas.
   - Establish an exotic vegetation management program.

A major stream restoration/rehabilitation and stormwater management project is proposed for the TRF tributary of Devils Hole Creek. This tributary has the greatest potential to support diverse and productive salmonid populations. The following rehabilitation project is recommended for the upper segment of the TRF tributary:

- Replace the Snook Road and parking lot access road culverts with bridges or arched culverts.
- Install step-pool LWD in the stream to enhance upstream fish passage and provide instream habitat.
- Enhance the riparian zone on the parking lot side with native trees and shrubs. Reclaiming a portion of the parking lot and widening the riparian corridor should also be considered. This parking area sees little use and reclaiming a wide, natural buffer here would also allow re-meandering the stream channel to maximize habitat functionality. Install natural streambank vegetation for stabilization throughout this tributary segment.
- Replace the Trigger Avenue culvert with a higher capacity, arched culvert.
- A stormwater treatment wetland should be constructed in the area between Trigger Avenue and the TRF complex. Road, rooftop, and parking-lot run-off from the Trigger Avenue and TRF areas should be routed to this treatment facility. The stream channel should be meandered around this constructed wetland. The stream channel in this section should be enhanced for salmonid passage to the upper reaches. Spawning and rearing should be a secondary goal for this segment. Stream-bank stabilization and revegetation will also be required. Bottomless, arched culverts should be installed under Trigger Avenue and Sturgeon Street.
- A portion of the current stormwater piping network for the TRF complex is routed directly into Devils Hole Creek. This practice should be discontinued as soon as possible. From both a water quality and a run-off quantity standpoint this is not acceptable. Any run-off not treated by the proposed constructed wetland facility (or all stormwater, if the facility is not built) should be routed to Hood Canal via biofiltration conveyance systems along Sturgeon Avenue.
- Riparian buffer zones should be established around all tributaries within the Devils Hole Creek watershed. These buffers should be marked to prevent encroachment and should be actively managed for mature, native (coniferous) forests. Buffers of 100 m are recommended, with a 30-m buffer established as the minimum allowable.

MILITARY INSTALLATION DATA SUMMARY
NAVAL COMMUNICATIONS STATION JIM CREEK

Naval Communications Station (NCS) Jim Creek is located northeast of Arlington in the Puget Sound region of western Washington (Figure 36). NCS Jim Creek consists of a total of just under 5,000 acres, of which about 80–90% is in native forest land-cover. The base is built at the edge of the Cascade Mountains of western Washington. Most of the adjacent land is within the Mount Baker National Forest, which is owned by the U.S. Forest Service (USFS). Timber harvest and rural residential are the main land uses in the surrounding area. Base elevation ranges from 500 to 3,000 feet.

The primary mission of the NCS Jim Creek is to provide long-range communications support to the operational USN forces in the Pacific Ocean; to maintain and operate facilities for administration and command functions; and to provide environmental and recreational services. NCS Jim Creek is the highest-powered very low frequency (VLF) radio transmission facility in the world.

The principal drainage on the NCS is Jim Creek, which has its headwaters about 4 miles northeast of the base in the Cascades (Figure 36). Outside the base boundary, Jim Creek is a high gradient stream, but within the base and further downstream, it has characteristics of a typical lowland stream. Upstream of the base, Jim Creek is primarily "step-pool" and "cascade" morphology, but within the base the creek consists of mainly low-moderate gradient "forced pool-riffle" morphology. Within the NCS, Jim Creek changes from a relatively wide, lowland valley to a confined, steep-walled valley structure. Two main tributaries of Jim Creek exist within the NCS jurisdictional boundaries (Figure 36). Hatchery Creek is a small, spring-fed tributary that begins on the southwestern slopes of Wheeler Mountain. Cub creek is a larger tributary stream that has its headwaters in a series of wetland lakes in the southern portion of the base. These three streams support multiple species of salmonids, including chinook, cutthroat, coho, and steelhead.

The underlying geology of the base consists of glacial till soils in the lower elevations and morainal material on the slopes and higher elevations. These soils and the steep slopes that exist within the base make the potential for landslides high. Several landslides exist on base, mostly where native forests have been cleared. The most unique feature of the NCS is the VLF "ground-field" antenna area. The location for the VLF radio station was originally acquired in 1949. The antenna array consists of ten catenary suspension spans, each between 6,000 and 9,000 feet in length that span the upper Jim Creek valley between Blue Mountain and Wheeler Mountain. The hillslopes below the antenna cables is configured as a ground field transmission zone, with cables running over the surface of the mountainside in a grid pattern. The entire ground field area has been cleared of trees and is maintained in this condition to support VLF transmission.

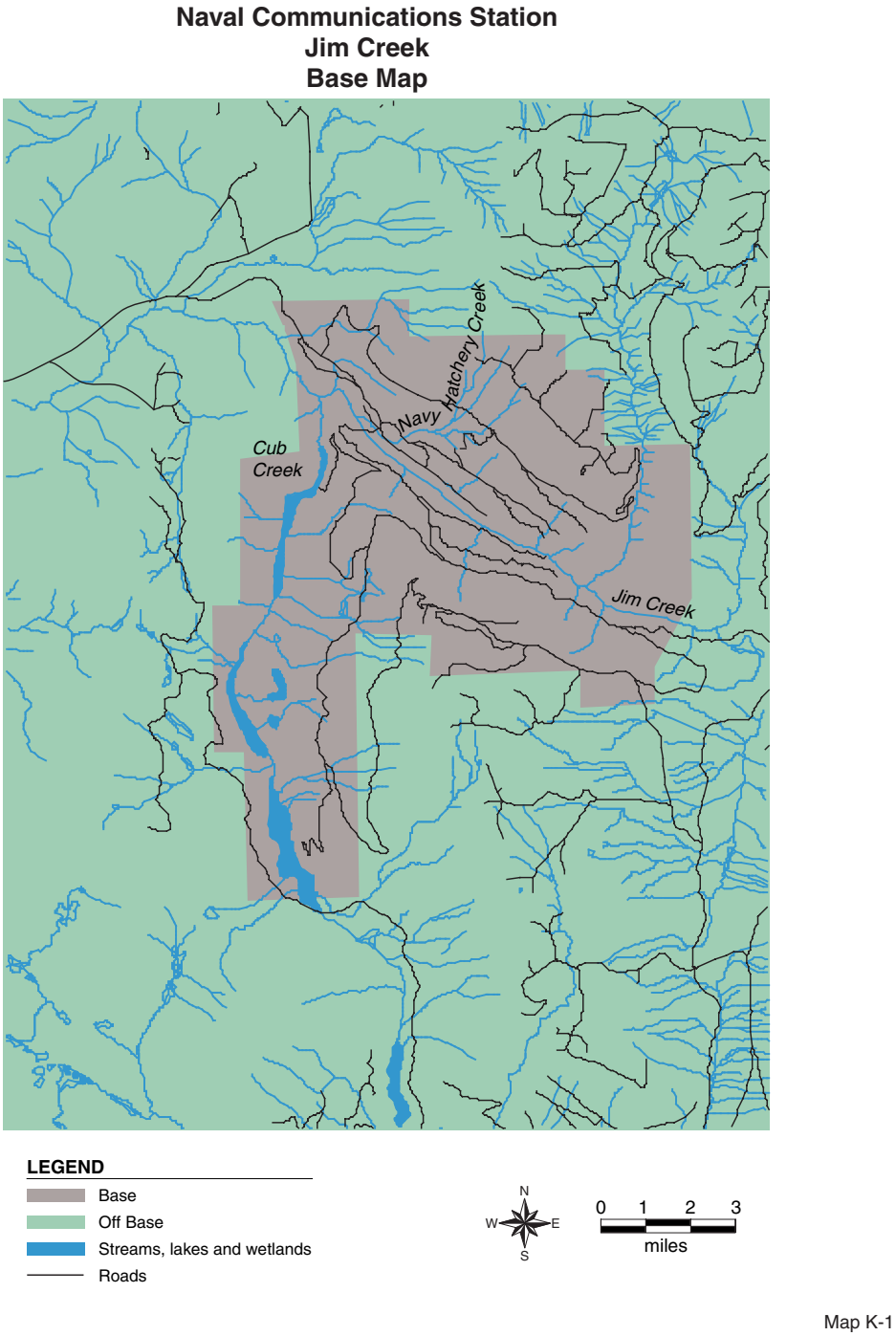

Figure 36. *Naval Communications Station Jim Creek base map*

The VLF antenna and ground field zone represent a military-unique land-use that is very uncommon at other DoD facilities and certainly is rare in the civilian sector. Essentially, there is an operational requirement to maintain the ground field clear of all vegetation other than groundcover or low shrubs (Figure 37). The ground field zone was first clear-cut in 1949 and has been maintained in that condition ever since. Due to the relatively unstable underlying soils and the steep slopes of the valley, this has created the potential

for major landslides and surficial erosion. There are also several access roads within the ground field area, which add to the landslide/erosion potential. Numerous landslide sites exist and erosional material has frequently washed into Jim Creek. These landslides and surface erosion problems also threaten the operational readiness of the system. An extensive network of drains was installed above the transmitter building on the slopes of Wheeler Mountain to prevent further erosion and landslide activity. Currently, aerial herbicide spraying is used to maintain the ground field free of undesirable vegetation. These practices are considered to be of limited effectiveness and do not support high water quality and biological integrity of Jim Creek. In addition, the transmitter access road and ground field vegetation control have directly impacted the stream channel and riparian corridor in upper Jim Creek. The middle section of Jim Creek passes through the NCS recreational camping area, then flows through the base administration and public works area before exiting the base. There is one pedestrian bridge and one road bridge crossing the creek on base.

Cub Creek is the largest tributary of Jim Creek on the station. The headwaters of this creek are in a series of wetland lakes located in the south end of the base. These lakes serve as a recreational fishing and boating area for naval personnel and their families. Both upper and lower Twin Lakes are stocked with rainbow trout. Below these lakes the Cub Creek meanders through dense riparian forest and a series of wetlands, both off-channel and riparian. Beaver are active in this section of the creek. The lower section of Cub Creek has been dammed to form a reservoir that serves as a back-up drinking water supply for the base. This system is rarely used. There is a fish-way built into the dam, but it does not appear to be passable by salmonids under all flow conditions. The lower reach of Cub Creek is fairly steep (4–6%) and has typical step-pool morphology. Cub Creek has excellent salmonid spawning and rearing habitat.

Hatchery Creek is a small tributary of Jim Creek that begins on the southwestern slopes of Wheeler Mountain. The upper reaches of this creek often go dry or hyporheic during summer low-flow periods. A salmon hatchery is located on this tributary.

The base is in compliance with the 1972 CWA and the 1987 WQA, but may not be in full compliance with NPDES Phase II requirements that are being finalized at this time (*Jim Creek NCS*, 1994). These laws established a framework for regulating the discharge of municipal and industrial stormwater under the National Pollutant Discharge Elimination System (NPDES) permit program as administered by the U.S. EPA. U.S. Navy environmental regulations and policies are stipulated in the Department of the Navy Environmental and Natural Resources Program manual (OPNAVINST 5090.1B). These regulations state that *Navy facilities must comply with all requirements of the CWA and must meet all applicable federal, state, and local stormwater permit requirements*. The use of the best available technology for reducing pollution is also stipulated.

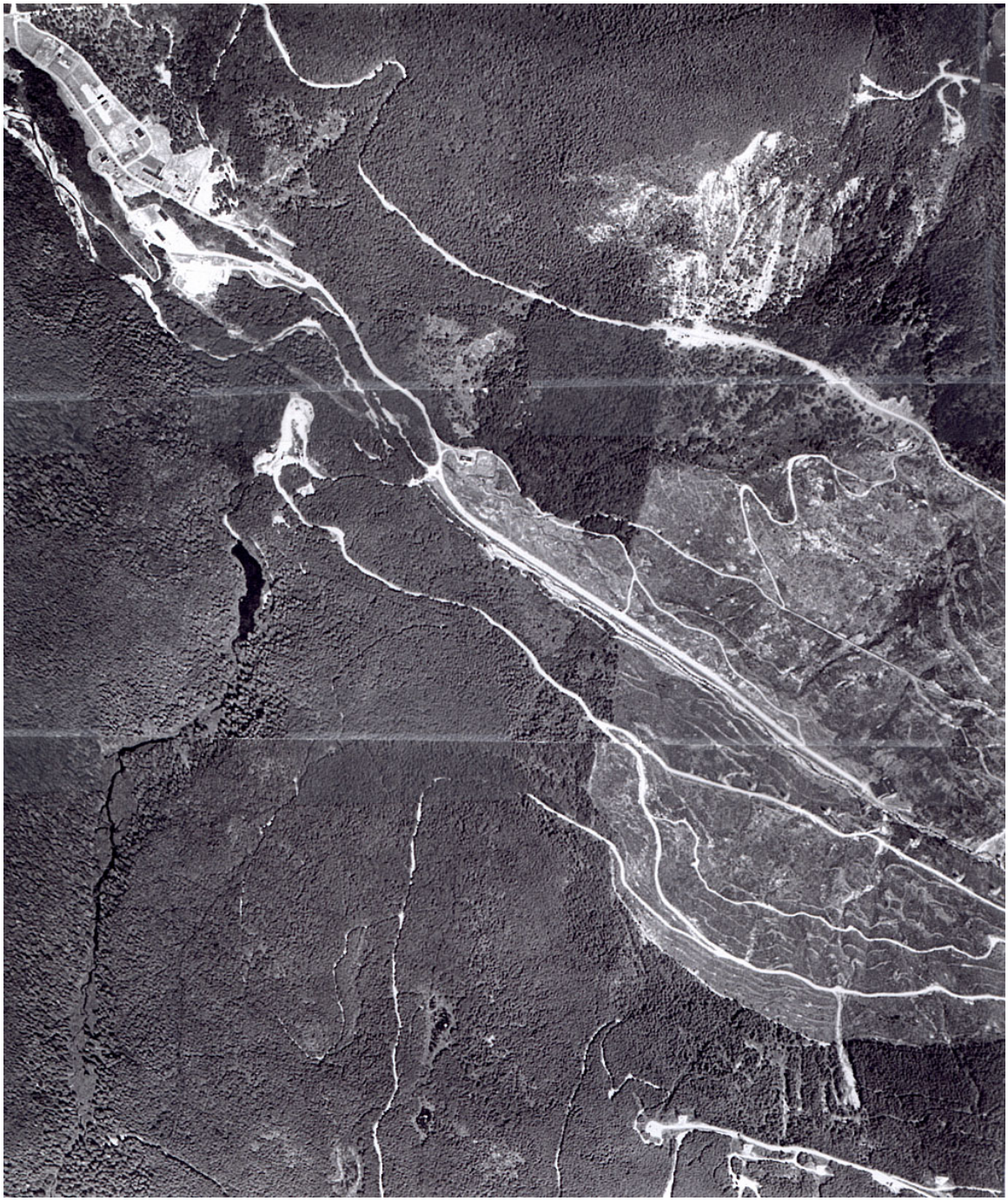

Figure 37. *Aerial photo of NCS Jim Creek showing ground-field area*

Jim Creek, Cub Creek, and Hatchery Creek Data Analysis

Watershed Characterization

Land-use within NCS Jim Creek is a mixture of military operational, administrative, and residential land uses (Table 23). However, outside of the administration area and the ground-field, the majority of the station is native forest land-cover, especially in the sub-

basin draining to Cub Creek. Most of the developed areas on base are located within the lower Jim Creek sub-basin on the east side of the base (Table 32).

Table 23. *Land-use and land-cover data for NCS Jim Creek (%)*[1]

Watershed	Total Impervious Area (TIA)	Native Forest	Native Grass	Bare Soil	Urban Forest	Urban Grass	Urban Paved
Jim Creek	**10**	77.0	4.5	0.0	15.7	2.3	0.5
Cub Creek	**8**	80.0	3.0	0.0	12.0	3.0	2.0

[1]Data is based on University of Washington Center for Urban Water Resources Management land-use and land-cover database. http://depts.washington.edu/cuwrm/research/landsat.htm

Basin Land-Use

- Table 23 summarizes the land-cover and land-use data for the Jim Creek and Cub Creek watersheds. NCS Jim Creek, as a whole, is approximately 9% impervious, including the developed areas and the ground-field area. Buildings, parking lots, and landscaped areas dominate the developed portions of the base.
- Road density within NCS Jim Creek is only 0.78 km/km^2 total. The road density in Cub Creek watershed is only 0.55 km/km^2 and only 0.83 km/km^2 in the area contributing to Jim Creek. Most of the roads on base are gravel, with the only paved roads being those serving the administration area, operational buildings, and the public works facility. Essentially all of the paved roads are located in the lower sub-basins of Jim, Cub, and Hatchery creeks. Generally, a road density over 3 km/km^2 is considered high and is expected to have a significant impact on aquatic resources (*May et al*., 1997).
- Extensive areas of native wetland, and mature coniferous forest still exist on the base. These areas contain a diverse array of native flora and fauna, including some endangered species.

Riparian Corridor Continuity

- JIM-1: The riparian corridor is relatively intact, with minimal fragmentation (one utility line crossing).
- JIM-2: The riparian corridor is intact, with no fragmentation.
- JIM-3: The riparian corridor is relatively intact, with minimal fragmentation (one road crossing).
- JIM-4: The riparian corridor is narrow and fragmented (sometimes non-existent) throughout the ground-field zone.
- CUB-1: The riparian corridor is intact, with no fragmentation.

- CUB -2: The riparian corridor is intact, with no fragmentation.
- HAT-1: The riparian corridor is relatively intact, with minimal fragmentation (one trail crossing).
- HAT-2: The riparian corridor is relatively intact, with minimal fragmentation (one road crossing).

Riparian Integrity

- JIM-1: The riparian forest is predominately deciduous forest (both mature and young). The riparian zone is relatively narrow, but intact. LWD recruitment potential is rated as fair. Invasive and exotic species (blackberries, reed canary grass, etc.) are present in patches, especially around the utility line crossing. Riparian integrity is poor for this segment.
- JIM-2: The riparian forest is predominately mixed conifer and deciduous forest (both mature and young). The riparian zone is relatively wide and intact. LWD recruitment potential is rated as fair to good. Invasive and exotic species (blackberries, reed canary grass, etc.) are present in patches. Riparian integrity is moderate for this segment.
- JIM-3: The riparian forest is a mixture of mature conifers and deciduous trees. However, due to the presence of the campgrounds on both sides of the creek, the riparian zone is narrow, but intact. LWD recruitment potential is rated as good. Riparian integrity is moderate for this segment.
- JIM-4: The riparian forest is predominately deciduous forest (both mature and young), with patches of mature conifers. This segment of the creek passes through the ground-field zone, therefore the riparian zone is very narrow and fragmented. LWD recruitment potential is rated as poor. Invasive and exotic species (blackberries, reed canary grass, etc.) are present in patches. Riparian integrity is poor for this segment.
- CUB-1: The riparian forest is a mixture of mature conifers and deciduous trees with a well-established understory and groundcover layers. The riparian zone is wide and intact. LWD recruitment potential is rated as good to excellent. Riparian integrity is high for this segment.
- CUB -2: The riparian forest is a mixture of mature conifers and deciduous trees with a well-established understory and groundcover layers. The riparian zone is wide and intact. LWD recruitment potential is rated as good to excellent. Riparian integrity is high for this segment.
- HAT-1: The riparian forest is a mixture of mature conifers and deciduous trees with a well-established understory and groundcover layers. The riparian zone is relatively wide and intact. LWD recruitment potential is rated as good to excellent. Riparian integrity is high for this segment.
- HAT-2: The riparian forest is predominately deciduous forest (both mature and young). The riparian zone is relatively narrow, but intact. LWD recruitment potential is rated as fair. Invasive and exotic species (blackberries,

reed canary grass, etc.) are present in patches, especially around the utility line crossing. Riparian integrity is poor for this segment.

Canopy Cover

- JIM-1: Canopy cover is poor in this segment in part due to the width of the stream channel and in part due to the lack of mature conifers in the riparian corridor.
- JIM-2: Canopy cover is poor in this segment in part due to the width of the stream channel and in part due to the lack of mature conifers in the riparian corridor.
- JIM-3: Canopy cover is good in this segment of the creek.
- JIM-4: Canopy cover is poor in this segment of the creek due to the lack of riparian vegetation in the ground-field zone.
- CUB-1: Canopy cover is good in this segment of the creek.
- CUB -2: Canopy cover is good in this segment of the creek.
- HAT-1: Canopy cover is good in this segment of the creek.
- HAT-2: Canopy cover is poor in this segment due mainly to the lack of mature conifers in the riparian corridor.

Large Woody Debris

LWD is a key structural feature in PNW streams. LWD is the main pool-forming element in lowland streams and is responsible for much of the natural channel complexity in these streams (*Maser et al*., 1988). The desired frequency of LWD for PFC is > 400/km, with < 200/km considered inadequate. This equates to a normalized target BFW-spacing of 2 pieces of LWD per BFW-length of stream channel (*Peterson et al*., 1992). Large, key pieces of LWD are especially important because they are relatively stable and provide long-term habitat as well as instream cover for salmonids. The PFC target for key LWD is generally considered to be > 50/km or about 25% of the total LWD.

- JIM-1: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was within the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also within the range expected for natural stream channels. In addition, 53% of the instream LWD was coniferous. However, only 11% of the LWD was classified as key. Channel complexity was moderate in this segment, as was LWD recruitment potential. The lack of key LWD was the most significant deficiency in this segment.
- JIM-2: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was within the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also within the range expected for natural stream channels. In addition, 96% of the instream LWD was coniferous. Approximately 23% of the LWD was classified as key. Channel complexity was moderate in this segment, as was

LWD recruitment potential. There were no significant deficiencies noted in this segment.

- JIM-3: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. In addition, none of the instream LWD was classified as key. Nearly all the instream LWD was coniferous. Channel complexity was generally low in this segment and the LWD recruitment potential was moderate. The lack of adequate instream LWD and lack of key LWD are the most significant deficiencies in this segment.
- JIM-4: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. However, over 27% LWD was classified as key and 83% of the instream LWD was coniferous. Channel complexity was generally low in this segment and the LWD recruitment potential was also low due to the lack of mature riparian vegetation throughout the ground-field zone. The lack of adequate instream LWD and the low LWD recruitment potential are the most significant deficiencies in this segment.
- CUB-1: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. However, over 35% LWD was classified as key and 90% of the instream LWD was coniferous. Channel complexity was generally high in this segment, as was LWD recruitment potential. The lack of abundant instream LWD was the most significant deficiency in this segment.
- CUB -2: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. However, over 33% LWD was classified as key and 97% of the instream LWD was coniferous. Channel complexity was generally high in this segment, as was LWD recruitment potential. The lack of abundant instream LWD was the most significant deficiency in this segment.
- HAT-1: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. However, 25% LWD was classified as key and nearly all of the instream LWD was coniferous. Channel complexity was generally moderate to high in

this segment, as was LWD recruitment potential. The lack of abundant instream LWD was the most significant deficiency in this segment.

- HAT-2: A majority of the LWD noted in the survey reach was interacting with the bankfull channel. The frequency of LWD was much lower than the desired range for PFC, as was the BFW-spacing. The average size of instream LWD was also below the range expected for natural stream channels. In addition, none of the instream LWD was classified as key. Nearly all the instream LWD was coniferous. Channel complexity was generally low in this segment and the LWD recruitment potential was also low. The lack of adequate instream LWD and lack of key LWD are the most significant deficiencies in this segment.

Rearing Habitat

Adequate high-quality rearing habitat (pools) is generally recognized as one of the critical factors limiting salmonid productivity. This is especially true of winter rearing habitat for juvenile coho salmon (*Brown and McMahon*, 1987; *Reeves et al*., 1989; *Nickelson et al*., 1992). LWD is probably the key component of salmonid rearing habitat in small streams in the PNW and is critical to over-winter survival of juvenile coho salmon (*Bustard and Narver*, 1975; *Brown and McMahon*, 1987; *McMahon and Hartman*, 1989; *Nickelson et al*., 1992). LWD not only provides habitat structure, complexity, and a high-flow refuge but is a major form of instream cover for young fish. Coho, in particular, have a strong preference for pools with a structurally complex (LWD) microhabitat (*McMahon and Hartman*, 1989). Cutthroat trout appear to prefer a similar rearing habitat, but may be more adaptable to less than ideal conditions (*Heggenes et al*., 1991). Watershed land use (development) has reduced the quantity of rearing habitat (pools) and degraded pool quality as well (Meehan, 1991). The pervasive and long-term nature of urbanization has been especially hard on instream habitat in general and on rearing habitat in particular (*Booth and Reinelt*, 1993). The PSL stream study showed a significant reduction in the quantity and quality of rearing habitat due to the cumulative effects of watershed development (*May*, 1996).

Rearing habitat typically mirrors the quantity and quality of LWD in the stream channel. PQI scores indicate the quality of rearing habitat in each pool. High quality pools are generally deep, large in size, and have abundant cover (LWD, overhanging vegetation, etc.). The NMFS MPI suggests 60–80 pools/km for PFC in streams with a bankfull width of 5–10 m. Pool BFW-spacing should be less than 2 (*Peterson et al*., 1992). In addition, the % pool habitat (by surface area) should be 40–60% for low gradient streams, such as the lowland streams in this study. RPD should be relatively deep to provide good cover and temperature refugia.

- JIM-1: Pool frequency, pool BFW-spacing, and the % pool habitat (10%) were all well below the MPI-target range. However, the average RPD was relatively deep (0.66 m) and the quality of pools in this segment was generally good (PQI = 4.2). This segment of the creek was classified as a plane-bed type channel and therefore little pool habitat would be expected even in a completely natural channel of this type. This section of the creek provides excellent spawning habitat for most salmonids and good rearing habitat for

steelhead and other salmonids that prefer faster water and do not require extensive pool habitat.

- JIM-2: Pool frequency, pool BFW-spacing, and the % pool habitat (37%) were all very close to the MPI-target range. In addition, average RPD was relatively deep (0.59 m) and the quality of pools in this segment was also good (PQI = 4.33).
- JIM-3: Pool frequency, pool BFW-spacing, and the % pool habitat (44%) were all very close to the MPI-target range. However, the average RPD was relatively shallow (0.23 m) and the quality of pools in this segment was generally poor (PQI = 1.67).
- JIM-4: Pool frequency, pool BFW-spacing, and the % pool habitat (22%) were all well below the MPI-target range. In addition, average RPD was relatively shallow (0.31 m) and the quality of pools in this segment was generally poor (PQI = 1.79). This segment of the creek flows through the ground-field zone and has been channelized to allow for the transmitter building and access road to be constructed. Little rearing habitat exists in this segment, channel complexity is low, and there is almost no LWD recruitment potential because of the lack of riparian forest corridor within the ground-field zone.
- CUB-1: Pool frequency, pool BFW-spacing, and the % pool habitat (22%) were all slightly below the MPI-target range. However, the average RPD was relatively deep (0.38 m) and the quality of pools in this segment was generally good (PQI = 3.78). This segment of the creek was classified as a step-pool type channel and therefore only limited pool habitat would be expected even in a completely natural channel of this type. This section of the creek provides excellent rearing habitat for most salmonids, especially those that prefer step-pool habitat (e.g., cutthroat and coho).
- CUB -2: Pool frequency, pool BFW-spacing, and the % pool habitat (43%) were all very close to the MPI-target range. In addition, average RPD was relatively deep (0.35 m) and the quality of pools in this segment was also good (PQI = 3.44). There are also extensive beaver ponds, off-channel wetlands, and riparian wetland-lakes within this segment (and throughout upper Cub Creek), making this excellent coho rearing habitat.
- HAT-1: Pool frequency, pool BFW-spacing, and the % pool habitat (14%) were all well below the MPI-target range. In addition, average RPD was relatively shallow (0.24 m) and the quality of pools in this segment was generally poor (PQI = 2.42).
- HAT-2: Pool frequency, pool BFW-spacing, and the % pool habitat (13%) were all well below the MPI-target range. In addition, average RPD was relatively shallow (0.24 m) and the quality of pools in this segment was generally poor (PQI = 2.17).

Spawning Habitat

RQI scores indicate the quality of spawning habitat in each riffle. High quality riffles have clean substrate, low embeddedness, and abundant instream cover. The % riffle habitat (by surface area) should be 40–50% for low gradient streams, in the PNW. For low-gradient (< 4%), pool/riffle streams like those found in the PSL region, spawning (riffle) habitat should comprise about 40–60% of the wetted surface area of the stream (*Peterson et al*., 1992). In addition to the quantity of spawning habitat, the quality of existing habitat is also important. The process of spawning site selection by female salmonids is not well understood (*Groot and Margolis*, 1991). However, there is a combination of factors that determine acceptability for most species. These include the size distribution of substrata particles, water depth, water velocity, gravel permeability (fine sediment content), streambed topography, and protective cover during the spawning process. The exact characteristics of acceptable spawning sites will depend on the species, the size of the female, and the number of acceptable sites available. Within the range of sites where spawning habitat is acceptable, female salmonids appear to apply a second set of criteria to select the optimum site for redd construction. The basis of this site selection is believed to be intragravel flow conditions favorable for incubation and development of embryos (*Crisp and Carling*, 1989). Suitable intragravel flow conditions occur where the infusion of oxygenated surface water into the streambed is enhanced by a combination of bed topography, instream hydraulic conditions, and gravel permeability. Pool tail-outs are most often identified as the optimum sites for redd construction because of the natural down-welling flow common to these areas.

Land-use activities such as timber harvesting, mining, grazing, and urban development can have a significant negative impact on spawning habitat, as can catastrophic natural events (e.g., floods or debris flows). Besides scouring and destruction of spawning areas due to high flows, probably the most damaging effect of human activity is the deposition of excessive fine sediment in spawning gravels (*Chapman*, 1988). To some extent, female salmonids have the ability to modify the streambed to improve the quality of spawning habitat by winnowing fine sediment from the redd during its construction. However, deposition of sediment after redd construction can significantly degrade the quality of the incubating environment. Excessive fine sediment has been associated with reduced survival to emergence of salmonids because of reduced intragravel water flow (*Chapman*, 1988).

- JIM-1: Spawning habitat quantity (62%) and quality (RQI = 3.0) were both within the PFC range in this survey segment.
- JIM-2: Spawning habitat quantity (63%) and quality (RQI = 3.2) were both within the PFC range in this survey segment.
- JIM-3: Spawning habitat quantity (56%) and quality (RQI = 2.5) were both within the PFC range in this survey segment.
- JIM-4: Spawning habitat quantity (79%) was higher than the desired PFC range and quality (RQI = 2.0) was below the PFC range in this survey segment. Again, the impacts of channel modification and the lack of riparian vegetation in the ground-field zone have resulted in degraded instream habitat conditions.

- CUB-1: Spawning habitat quantity (69%) and quality (RQI = 4.0) were both within the PFC range in this survey segment.
- CUB -2: Spawning habitat quantity (36%) was close to the PFC range as specified by the NMFS MPI criteria and spawning habitat quality (RQI = 4.0) was also within the PFC range in this survey segment.
- HAT-1: Spawning habitat quantity and quality were both within the PFC range in this survey segment. However, the channel was hyporheic in much of the segment, especially in the upper reaches.
- HAT-2: Spawning habitat quantity and quality were both within the PFC range in this survey segment. However, the channel was hyporheic in much of the segment, especially in the upper reaches.

Habitat Quality Index (HQI)

The habitat quality of the assessed segments of Jim, Cub, and Hatchery Creeks (Appendix K) was evaluated using the HQI. The summed score of eight metrics determined the final HQI score (see results section for details). In addition, streambank stability was generally found to be good throughout Jim, Cub, and Hatchery Creeks, indicating that excessive stormflows are not a major watershed problem.

- JIM-1: HQI = 32 (Good)
- JIM-2: HQI = 39 (Good)
- JIM-3: HQI = 24 (Fair)
- JIM-4: HQI = 24 (Fair)
- CUB-1: HQI = 34 (Good)
- CUB -2: HQI = 41 (Excellent)
- HAT-1: HQI = 31 (Good)
- HAT-2: HQI = 24 (Fair)

Instream salmonid habitat was very good throughout the Jim Creek stream system, including Cub and Hatchery creek tributaries. LWD was generally plentiful and of good quality, although key pieces were lacking in some segments. Middle and upper Cub Creek contains especially good spawning and rearing habitat for both coho salmon and cutthroat trout. The lower part of Cub Creek also contains good salmonid habitat. However, the dam that was built to create the Cub Creek reservoir is a significant barrier to salmonid migration, even with the existing fish-way. It is strongly recommended that this barrier be corrected as soon as possible and coho be restored to Cub Creek. Hatchery Creek probably would support coho and cutthroat populations, even with it's low summer baseflow conditions and even without the presence of the hatchery. It is recommended that targeted LWD installations be considered for lower Hatchery Creek to enhance rearing habitat and instream habitat complexity. In addition, the hatchery operations should be re-evaluated with respect to their ecological benefits and costs. The mainstem of Jim Creek also contains good salmonid habitat, although targeted LWD installations could improve conditions. The most significant problem noted is the long-term impacts

of the ground-field zone on riparian and instream habitat-forming processes (i.e., LWD recruitment, streambank stabilization, etc.).

Biological Integrity

In general, the biological integrity of streams on NCS Jim Creek was found to be within the natural range. In most cases, the B-IBI scores were in the "good" range (Appendix K). It is strongly recommended that a biological monitoring plan be established for NCS Jim Creek. This plan should utilize benthic macroinvertebrates as the indicator organisms and should utilize a multi-metric index for analysis. The B-IBI developed by *Karr* (1996) for the PNW, and used in this study, is recommended.

- JIM-1: B-IBI Score = 32 (Fair)
- JIM-2: B-IBI Score = 40 (Good)
- JIM-3: Not Sampled
- JIM-4: Not Sampled
- CUB-1: B-IBI Score = 34 (Fair)
- CUB -2: B-IBI Score = 38 (Good)
- HAT-1: B-IBI Score = 36 (Good)
- HAT-2: Not Sampled

Chemical Water Quality

This study did not specifically assess chemical water quality. Analysis of data taken as part of the current SWPPP indicates that chemical composition of the water is acceptable by US EPA and Washington Department of Ecology standards.

Recommendations

1. Management of the ground-field zone and the mainstem of Jim Creek should be re-evaluated in light of the significant, long-term negative impact this military-unique activity is having on Jim Creek and its aquatic resources. The current NCS Jim Creek master plan (*NCS Jim Creek*, 1984) noted that this antenna ground-field has resulted in a degradation of salmonid spawning habitat due to fine sediment deposition from hillslope erosion, landslides, and streambank instability. It is strongly recommended that the current vegetation management strategy, which relies heavily on the periodic use of aerial herbicide application, be discontinued. In addition to the negative impacts on physical habitat already noted in this report, there could be significant chronic, long-term chemical impacts of this activity on aquatic and terrestrial biota. An alternative ground-field management strategy should include establishment of native groundcover and other suitable low-growing vegetation. Removal of trees and other undesirable vegetation should be accomplished by hand trimming and/or localized, spot-application of an environmentally safe herbicide. The master plan also calls for the possible use of controlled burning as a vegetation management tool. This option should also be investigated for feasibility and effectiveness. In addition to the ecological effects discussed above, hillslope erosion and mass-wasting events (landslides) can potentially have an impact on the operational capability of NCS Jim

Creek. A slide could damage the transmitter building, access road, and ground-field antenna. A more ecologically sound ground-field management strategy will not only enhance physical habitat within the upper Jim Creek sub-basin, but will also improve long-term mission accomplishment.

2. The mainstem of Jim Creek upstream of the main road crossing and downstream of the transmitter building should be targeted for a major instream and riparian rehabilitation project. Because of the constraints of the ground-field operational requirements and the encroachment of the access road, there is a limit as to what can be accomplished, but some enhancement is possible. The riparian corridor should be planted with native vegetation that will provide some functional support for the stream, while still remaining within the limits of the ground-field restrictions. Shade, cover, sediment capture or filtration, and streambank stability are the primary functional attributes of concern. The installation of LWD and/or boulders should be considered to enhance instream rearing habitat and provide instream flow refugia. Relocation of the access road to higher ground and removal of road fill could allow for the restoration of some natural floodplain/CMZ functionality, but this would be a significant (and costly) undertaking. This channel is a natural plane-bed channel type with elements of both a step-pool and forced pool-riffle morphology. Instream rehabilitation can therefore utilize elements of each stream type. The use of very large or key LWD as well as boulders should be considered to create instream complexity, roughness elements, and local refugia habitat. Re-establishing a functional riparian corridor should be the top priority. In addition to the erosion problems discussed above, there may be temperature issues with this section of Jim Creek.

   The NCS master plan (*Jim Creek NCS*, 1994) calls for a hydroelectric power plant to be built on the middle mainstem of Jim Creek. This proposal would likely have a significant impact on salmonid migration and should be dropped.

3. Owing to its currently undeveloped condition, the Cub Creek sub-basin should be designated as a resource conservation area. With the exception of the current low-impact recreational uses, development within this catchment should be excluded or severely limited. The watershed should be managed for resource protection, with only low levels of recreational activity allowed. Selective timber harvest in the upland sections of the catchment may be allowed but only if it is greater than 100 m (300 ft) from any perennial or seasonal stream channels, wetland areas, and steep slopes. Because the headwaters of this stream are located off base, a close coordination with USFS and private landowners will be required to protect the downstream portions of the creek.

   All segments of Cub Creek are in a relatively natural condition. The riparian corridor is relatively intact, quite wide and dominated by mature forest and wetlands. There is very little streambank erosion or streambed scour, resulting in good spawning habitat throughout the creek. Beaver are also active in the Cub Creek drainage, creating ponds and providing excellent rearing habitat. Conservation and enhancement of this refugia area should be the primary strategy for aquatic resource management within NCS Jim Creek.

4. The reservoir dam on lower Cub Creek should be removed and a natural channel restored to this section of the creek. This will require instream habitat construction, riparian restoration, and wetland revegetation. An alternative back-up drinking water source should be established prior to dam removal (perhaps a well or another rainwater catchment device in upper Jim Creek). It is likely that a significant quantity of sediment will need to be removed during this operation. As an alternative, a new fish ladder could be constructed around the dam to allow upstream migration of coho salmon and cutthroat trout. The main disadvantage of this option is the long-term maintenance that will be required to ensure passage in all flow conditions.

5. Hatchery operations in Hatchery Creek should be evaluated for their impact on native salmonid populations. WDFW and tribal biologists should be consulted on this issue prior to revising the hatchery management plan.

6. It is recommended that stewardship of Jim, Cub, and Hatchery creeks include the following:

    - Installation of a flow gage at the mouth of the creek to monitor changes in the hydrologic regime.
    - Long-term riparian plantings of native cedar, hemlock, cottonwood, and spruce.
    - Develop and implement a short-term LWD strategy until full riparian function is achieved.
    - Conserve native forest throughout the watershed and minimize impervious surfaces in all developed areas.
    - Establish an exotic vegetation management program.

DISCUSSION

The cumulative impacts of land-use practices over the past century, including timber harvest, agriculture, and urbanization, have significantly modified the natural landscape characteristics of PSL watersheds, thereby altering many processes that maintain the natural structure and function of aquatic ecosystems. Due to increased population in the region, development has emerged as the most significant land-use in the lowland region today. As was discussed in the introduction to this report, the effects of watershed urbanization on aquatic resources are well documented and include extensive changes in basin hydrologic regime, channel morphology, instream habitat complexity, and physio-chemical water quality. The cumulative effects of these alterations on natural ecosystem structure and function have produced an instream habitat that is considerably different from that in which salmonids and other aquatic biota have evolved. In addition, development pressure has negatively impacted riparian forests and wetlands, which are an integral component of PSL stream ecosystems. Add to these ubiquitous, development-related impacts, the military unique impacts detailed in the previous sections, and it is understandable how and why the streams on DoD installations in the Puget Sound region are experiencing the problems they are.

Watershed Land-use and Hydrologic Regime

One of the most influential factors affecting instream habitat is modification of the natural landscape. In the PSL, there has been a significant shift from coniferous-dominated, forested watersheds to developed watersheds dominated by roads, buildings, and other impervious surfaces. In all but the most remote sites, native forest cover was significantly reduced from pre-settlement natural conditions in all the watersheds assessed in this study (Table 16). Land development or human activities that eliminate hydrologically mature forest cover and undisturbed soil can result in significant changes to stream flow regime and, in turn, to the physical stability of stream channels, as well as instream habitat complexity. These changes are manifested in altered stream flow patterns with higher volumes of storm flow, leading to accelerated channel erosion and habitat simplification.

Although factors other than hydrologic change (e.g., chemical water quality) can undoubtedly affect the magnitude of the cumulative impacts, the breadth of the existing data suggest that improvements in these other factors can never fully mitigate the hydrologic and physical consequences of watershed development. Under low levels of development (< 20% TIA), the magnitude of observed forest-cover losses affects watershed flow regime as much as, or more than, associated increases in impervious area. Empirical data from regional studies demonstrate a good correlation between stream channel morphological changes and habitat degradation and changes in flow regime that correspond to loss of about one-third of the forest cover in a typical western Washington watershed (*May et al.*, 1997; *Horner and May*, 1999; *Booth et al.*, 2001). A similar degree of observed damage also correlates to a level of watershed imperviousness (% TIA) of about 10%. These levels where significant changes are easily observed should not be mistaken for thresholds to be used as management tools. The most commonly chosen threshold values, maximum 10% TIA and minimum 65% forest cover, simply mark an observed transition zone from minimally to severely degraded stream conditions

for a typical PSL stream. This is not to say that all watersheds with > 65% forest cover and/or < 10% imperviousness will not display any signs of development impact.

All watersheds or streams are unique and each will respond differently to similar levels or types of human disturbance. At lower levels of human disturbance, aquatic-system damage may range from slight to severe but is nearly everywhere recognizable with appropriate monitoring tools. Not every watershed responds equally to a given level of human disturbance, but some degree of measurable resource degradation can be seen at virtually any level of watershed development. For any given watershed, additional human activity tends to produce additional aquatic-system degradation. However, these impervious and forest-retention percentages have proven to be attractive regulatory thresholds and are even being advocated by agencies and jurisdictions as necessary conditions for mandated protection of rural areas under the ESA. Once again, this is nothing more than an attempt to simplify a complex, multi-dimensional problem into a "one-size-fits-all" regulatory solution. Imperviousness and natural vegetative cover are certainly useful indicators of watershed conditions, but they are not a panacea for conservation or land-use management (Figure 38).

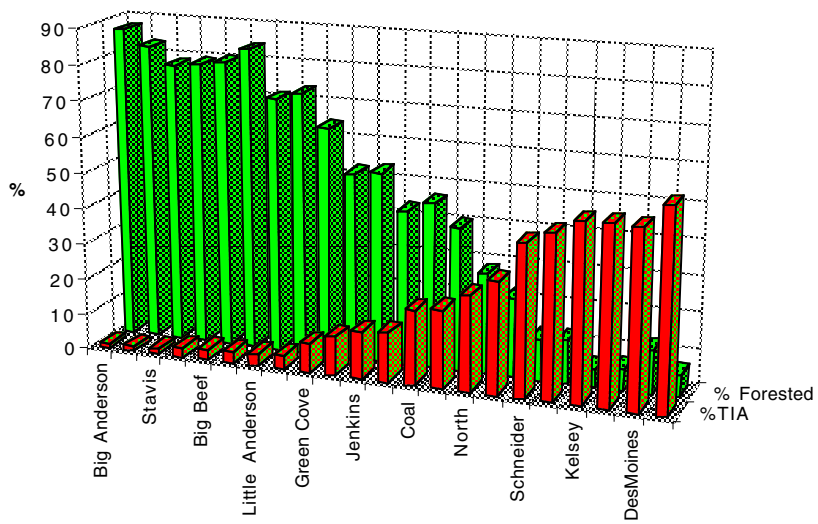

Figure 38. *Native forest cover and total impervious area (% TIA) in watersheds of the Puget Sound lowland eco-region (from* May et al.*, 1997)*

In spite of the shortcomings outlined above, the quantity and location of impervious surfaces are important factors to be considered in any development. Minimizing imperviousness, especially the effective impervious area (EIA), or that which is hydrologically connected to the stream-wetland network, will reap large rewards as far as reducing run-off volume and NPS pollution are concerned. Research in the PSL region suggests that maintaining forest cover may be even more important than limiting impervious area, at least at rural levels of development where zoning often effectively limits the range of imperviousness to under 10% TIA (*Booth et al*., 2001). In the absence

of land clearing limitations, forest cover can range between 5% and about 85% in watersheds with the same level of imperviousness.

In the PNW, reducing native forest cover will result in increased stormwater run-off and a loss of groundwater recharge. Increased run-off can lead to hillslope erosion and downstream channel instability. Clear-cutting, agriculture, and rural-residential are the most common land uses that represent the low imperviousness and low forest-cover category, but there are also military unique situations that have similar characteristics. The NCS Jim Creek antenna ground-field and the artillery impact areas at Fort Lewis are best examples of this condition. Obviously, limiting impervious surfaces alone is not sufficient to effectively protect aquatic resources. Consequently, even if both types of land-cover control (i.e., forest retention and impervious limitation) are critical to protect stream conditions, current land-use practices suggest that mandating retention of forest cover is the more pressing regulatory need in the lower end of the development spectrum. Degraded watersheds < 10% TIA and < 65% forest cover, are common in the PSL region and the great majority of the streams draining these areas are significantly degraded.

The apparent correlations between biological integrity, water quality, instream habitat quality, or stream channel stability and both impervious-area and forest-cover present a dilemma for watershed managers. On the one hand, these correlations point to tangible and defensible criteria for achieving a specific management objective, namely protecting the ecological integrity of aquatic resources. On the other hand, this objective, however worthy, still allows for the high probability of serious and significant aquatic-system degradation. Moreover, as development is allowed to approach these clearing and imperviousness levels, some level of degradation is virtually assured. The "apparent threshold" implied by these findings is simply the wrong type on which to manage for resource protection. This combination of imperviousness and forest cover does not separate a condition of no impact from that of impact, but instead, they separate the condition of some impact from that of gross and easily observed impact within the stream ecosystem (*Booth et al*., 2001). Ecologically speaking (hydrologically, biologically, chemically, and physically) there is no really negligible amount of watershed development (*May et al*., 1997; *Horner and May*, 1999; *Morley*, 2000; *Booth et al*., 2001). This appears to be the case even though our perception of, and our tolerance for, many of the associated changes in streams appear to undergo a relatively abrupt transition around the above-indicated level of development. It must be acknowledged that almost every increment of cleared land, and impervious surface constructed, is likely to result in some degree of resource degradation or loss. The decision of how much is acceptable is thus as much a social-political decision as a scientific one, perhaps even more so.

Therefore, watershed development of any type, whether conventional or military unique, should conserve the natural landscape and mimic natural hydrologic conditions as much as possible. If native vegetation must be cleared for a specific land-use (i.e., artillery impact area, ground-field antenna zone, etc.), then disturbance of native soils should be minimized (e.g., avoid compaction and/or removal of upper soil layers) and a suitable groundcover should be planted to minimize erosion and stormwater run-off.

Underlying the changes in basin hydrologic regime are the modifications to the natural drainage network that result from urbanization. Watershed development adds numerous artificial channels to the natural stream system. The most common of these are road-

crossings (along with roadside drainage ditches) and stormwater outfalls. These new channels are the main conduits by which stormwater from impervious surfaces is routed to the natural stream channel network. These artificial channels are typically more direct than natural ephemeral channels or swales they often replace, resulting in a significant reduction in lag-time between precipitation and streamflow response. In addition, natural depressional storage areas (wetlands, swales, etc.) are often graded or filled. As a result, there is also little or no infiltration or storage involved with these artificial stormwater routing systems and so the volume of run-off is dramatically increased. At the same time, many of the natural swales and ephemeral channels (and even many first-order channels) are lost to re-grading and construction, reducing the natural DD. The implication is clear, in addition to the effects of imperviousness the artificial, developed drainage network has an equally significant impact on basin hydrologic regime. *Graf* (1977) first discussed this in the mid-1970s and little has changed.

Studies of DD changes in basins undergoing timber harvest activities have also demonstrated a significant alteration in hydrologic and erosion processes due to road-related drainage (*Montgomery and Dietrich*, 1989; *Eaglin and Hubert*, 1993; *Montgomery*, 1994; *Wemple*, 1994). *Wemple* (1994) found that logging-road systems could increase DD from 36–60%. This DD increase corresponds to the 50% increase found in the PSL region when predominant land-use shifts from rural to suburban (*May et al.*, 1997). This represents a major change in the natural hydrologic regime and is an important underlying cause for many of the problems common to urban streams. In developing watersheds, stream channels are still routinely used as a conduit for untreated and uncontrolled stormwater run-off. Land-use planning should include not only control of impervious surfaces and native land-cover, but must address changes to the drainage network as well. Limiting the number of road-crossings and eliminating direct stormwater connections to the stream system should go hand-in-hand with efforts to reduce impervious surfaces.

For the most part, watershed landscape conditions within the DoD installations assessed during this study reflect the land-use conditions found throughout the Puget Sound region. With the exception of a few "military-unique" activities (i.e., Fort Lewis artillery impact area, McChord AFB runway/flight-line, and NCS Jim Creek antenna ground-field zone), the types of land-use found within the base were very similar in pattern and intensity to those present in the surrounding communities (Table 16). In contrast to most developing areas of Puget Sound, significant natural areas have been set aside for conservation and protection on DoD installations (i.e., NSB Bangor, NCS Jim Creek, and Fort Lewis). These open-space conservation areas serve multiple purposes, including wildlife habitat, recreational areas, and buffers between military operational activities and conventional land uses (residential, commercial, etc.). In general, those DoD facilities with watersheds retaining a majority of native landscape in a conservation status had the highest ecological integrity.

The conditions described above emphasize the need to develop new approaches to mitigate the consequences of watershed urbanization on streams. Even with stormwater BMPs, instream hydrologic patterns are substantially different from those to which native biota have adapted. These changes in the natural hydrologic regime cannot be completely mitigated with structural measures, such as engineered BMP facilities, alone (*Horner and*

May, 1999; *Booth et al*., 2001; *Horner et al*., 2001). Instead, control of watershed land-cover changes, including limits to both imperviousness and clearing, will need to be incorporated into watershed management plans. If developing watersheds are not designed to hydrologically mimic native, forested watersheds, then degradation of aquatic ecosystems is likely inevitable. If these necessary land-use limitations run counter to other, even more pressing social goals, most notably those to accommodate additional population growth or military operations, then our goals for aquatic-resource conservation need to be modified in these designated watersheds. By not acknowledging the need for such trade-offs, opportunities to discover the most sensible and effective strategy for protecting aquatic ecosystems will continue to be lost.

Chemical Water Quality

Over the past few decades, regulations and technological developments have largely eliminated point source discharges to receiving waters. As a result, the relative contribution of NPS pollution has steadily increased. Stormwater run-off is the most important NPS source in the urbanizing environment. Stormwater run-off typically contains a wide variety of chemical constituents at concentrations often exceeding water quality criteria or standards (*Chandler*, 1995). However, it is rare that significant impairment of beneficial uses of receiving waters result due to chemical water quality violations alone. Numerous studies have documented the impact of stormwater on stream quality (*Griffin et al*., 1980; *Pitt and Bozeman*, 1982; *Field and Pitt*, 1990; *Bannerman et al*., 1993; *Makepeace et al*., 1995; *Pitt et al*., 1995). The composition and level of pollutants in urban run-off can vary considerably depending on geographic location, climate, land-use patterns, and stormwater treatment. Stormwater can contain a variety of potentially harmful constituents, but most of these are found in non-toxic and/or are not bio-available for the most part. Further, because of the limited exposure duration of storm run-off events, major impairment of aquatic organisms or acute effects such as death has seldom been observed in the PSL region (*USGS*, 2000). However, long-term (chronic) exposure to stormwater pollutants may be a problem, but there is not enough data to make a judgment on this at this time. Instream chemical water quality and stormwater quality was not measured directly during this study, but no evidence of chemical water quality problems or severe water pollution problems were noted during field surveys.

Riparian Integrity

Aquatic ecosystems (rivers, streams, and wetlands) are very closely linked, ecologically, with their surrounding terrestrial ecosystems (*Willson et al*., 1998). The transition zone between the purely aquatic ecosystem and upland, terrestrial habitat is commonly referred to as the riparian ecotone (*Naiman et al*., 1988). The term ecotone implies a zone of transition from one ecosystem to another. It also implies that this zone is ecologically important to both adjoining ecosystems. This is certainly true of the stream-riparian ecosystems of our region (*Knutson and Naef*, 1997). In most streams and wetlands of the PNW, the riparian community (vegetation and wildlife) directly influences the physical, chemical, and biological conditions of the aquatic ecosystem. In turn, the aquatic system affects the structure and function of the riparian community. Nowhere is this more apparent than the importance of the riparian forest to salmonid habitat and the

contribution of salmon carcasses to the ecological integrity of the surrounding forests (*Cederholm and Peterson*, 1985; *Cederholm et al*., 1989; *Willson and Halupka*, 1995; *Willson et al*., 1998).

A nearly continuous corridor of mature, coniferous-dominated forest characterizes the natural riparian ecotones of the PNW region (*Gregory et al*., 1991). The ecosystem is made up of a complex multi-layered forest with western red cedar, western hemlock, and red alder as the dominant tree species (*Naiman and Bilby*, 1998). The riparian forest also includes a complex, dense, and diverse understory and groundcover vegetation. In addition, the extensive upper soil-layer of forest "duff" provides vital water retention and filtering capacity to the ecosystem. In the PNW, a typical natural riparian corridor also includes the stream or river floodplain, as well as numerous riparian or off-channel wetlands. Natural floodplains and riparian wetlands are critical components of a properly functioning aquatic ecosystem (*Naiman and Bilby*, 1998). Organic debris and vegetation from riparian forests also provide a majority of the organic carbon and other nutrients that supports the aquatic ecosystem food web in our small lowland streams. In addition to the characteristics of the riparian forest described above, the most commonly recognized functions of the riparian corridor include:

- Providing canopy-cover shade necessary to maintain cool stream temperatures required by salmonids and other aquatic biota.
- Stabilizing streambanks, minimizing streambank erosion, and reducing the occurrence of landslides. The roots of trees and other riparian vegetation provide the bulk of this function.
- Reducing fine sediment input into the stream system through floodplain retention and filtering.
- Filtering and vegetative uptake of nutrients and pollutants from groundwater and surface run-off.
- Providing a source of large woody debris (LWD) into the stream channel. LWD is the primary instream structural element, which functions as a hydraulic roughness element to moderate streamflows. LWD also as serves a pool forming function, providing critical salmonid rearing and refuge habitat. In addition, abundant LWD increases instream habitat diversity.
- Regulation of microclimate in the stream-riparian corridor.
- Providing critical wildlife habitat including migration corridors, feeding and watering habitat, and refuge areas during upland disturbance events.

Historically, the abundance of wild salmonids returning to spawn in PNW rivers and streams was prodigious (*Nehlsen et al*., 1991). The diversity of species supported by even small watersheds was also quite impressive. Anadromous salmonids provide a rich, seasonal food resource that directly affects the ecological integrity of both aquatic and terrestrial food webs. This is particularly true of the stream-riparian community. The potential contribution of nutrients from decomposing salmon carcasses to the forest is significant (*Willson et al*., 1998). Numerous terrestrial species, including eagles, bears, otter, raccoon, and a diverse array of birds, utilize salmon as an important seasonal food

resource. Many of these creatures have been know to haul salmon carcasses up onto streambanks, into the floodplain, and far into the surrounding forest (*Cederholm et al*., 1989). Salmon carcasses also are an important seasonal input into the food web of the aquatic community. Benthic macroinvertebrates, stream fish, and salmonid fry themselves utilize this nutrient-rich resource (*Cederholm and Peterson*, 1985). The ecological importance of this seasonal exploitation of salmon to specific consumers and the ecosystem as a whole has just begun to be researched in detail. It is, however, obvious that the presence of this seasonally abundant nutrient resource has had a hand in shaping the evolution of the stream-riparian ecosystem of the PNW. In turn, consumers and predators have likely exerted a reciprocal evolutionary influence on the life history of salmonids (*Willson et al*., 1998). Therefore, any human impacts that destroy or degrade habitat in the stream-riparian corridor, or reduce the abundance and diversity of wildlife that are associated with anadromous salmonids, has the potential to weaken or break the ecological linkages in this complex ecosystem food web. Considering that all species of salmonids and over 85% of Washington's terrestrial vertebrate species utilize stream-riparian habitat at some stage of their life-cycles, it is not difficult see the importance of these areas (*Knutson and Naef*, 1997). It has been estimated that between 50% and 90% of our riparian forests have been lost or significantly degraded by human land-use activities, making restoration and enhancement of stream-riparian ecosystems a high priority (*Knutson and Naef*, 1997). During regional studies of Puget Sound lowland watersheds, it also became apparent that these so-called riparian "buffers", if designed and maintained so as to emulate natural riparian conditions, could have a significant mitigating influence on the ecological degradation of streams and wetlands in watersheds undergoing development (*May et al*., 1997). This was reflected in higher than expected levels of biotic integrity in those stream reaches with wide, continuous, and naturally vegetated riparian corridors.

Based on the results of the initial PSL stream studies (*May et al*., 1997), the term, *riparian integrity* was adopted to describe the conditions found in natural PSL stream-riparian ecosystems. These "properly functioning conditions" should serve as a template for conservation and recovery of riparian areas. As used here, riparian integrity includes both structural and functional elements characteristic of the natural stream-riparian ecosystem.

Buffer width or extent (% corridor > specified width) is often the sole criteria by which most stream-riparian corridor management areas are generally defined. Impacts of human activities on stream-riparian ecosystems are numerous and highly variable. The complex mosaic of land use in developing watersheds results in a multiple stressors impacting the stream-riparian ecosystem. The characteristics of the stream-riparian ecosystem will also influence the extent and intensity of the human-induced disturbance. Streams in watersheds dominated by rural development will have different impacts than those in suburban or urban watersheds. Variables such as stream size, location within the watershed, stream gradient, valley configuration, watershed topography, soil type, and others all combine to make some stream-riparian ecosystems more or less sensitive to surrounding human impacts. For example, a stream with an extensive floodplain area or active channel migration zone (CMZ) will react quite differently than a stream within a deep, steep-walled ravine. It stands to reason then, that appropriate buffer size will depend on the spatial area necessary to maintain the desired riparian functions and on the

land-use activities that are influencing the stream-riparian ecosystem. It also stands to reason that a wider buffer may be required in situations where high-intensity land-use is found, than in areas of low-intensity land-use. Similarly, all else being equal, a sensitive tributary stream used by salmonids for spawning and rearing may require larger buffers than does a mainstem stream used only as a migration corridor. In general, urban riparian buffers have not been consistently protected or well managed (*Schueler*, 1995).

Of equal importance to the width or extent of the riparian corridor is the quality of the riparian area in terms of vegetation type, species diversity, physical condition, and maturity. Ideally, the riparian corridor in a developing or developed watershed should mirror that found in the natural ecosystems of that region. Due to the cumulative impacts of past and present land-use, this is often not the case. The *riparian quality* of the stream corridor is as important as the width or extent in determining how well a particular riparian area performs all of the functions required of it. The current vegetative composition and maturity should be factored into any riparian management or buffer width design effort. Areas dominated by mature, naturally complex forest have a much higher conservation potential than disturbed areas, young stands of native forest, or exotic vegetation. These mature and naturally diverse riparian areas also perform their required functions more efficiently and tend to be more resilient in recovering from disturbance (*Naiman and Bilby*, 1998). Past land-use activities in the PSL (timber harvest, road construction, and agricultural activities) have significantly impacted the riparian forests of the region (*Horner and May*, 1999). As a result, many riparian forests in urbanizing watersheds are dominated relatively young stands of alder and maple rather than the mixed-mature forests that characterize natural riparian communities of the PSL.

Floodplain connectivity is also critical to a properly functioning stream-riparian ecosystem (*Rapp*, 1997; *Naiman and Bilby*, 1998; *FISRWG*, 1998). This means that the active CMZ and floodplain should be included in the designated RMZ. Both from an ecological and public safety perspective, development should be excluded from the RMZ. In general, encroachment of developing areas should be prevented from impacting the structure or function of the stream-riparian ecosystem. This can be done via public education and by clear delineation of the RMZ (*Schueler*, 1995). In most lowland streams and rivers, the floodplain is an integral part of the stream-riparian ecosystem. Because of the dynamic equilibrium of stream systems, all streams have a characteristic CMZ. Due to natural topography and geomorphology, some streams are constrained to narrow valleys or ravines. These streams typically have a smaller floodplain and a constrained CMZ. For the purposes of designating riparian buffers, streams prone to channel migration, those with a history of channel migration over the past 100 years, and streams with a well-defined floodplain need to be identified. The floodplain or CMZ is then used as the starting point for riparian buffer delineation. Streams within ravines or no CMZ/floodplain should have their riparian buffers measured from the edge of the bankfull channel. A floodplain is defined as the low gradient area immediately adjacent to the stream or river channel. This area begins at the edge of the bankfull channel and typically receives overbank flows during larger storm events. The frequency of inundation depends on the size of the stormflow event and the topography of the floodplain. The 100-year flood is often used as the defining flood flow for purposes of delineating the nominal extent of the floodplain (*Dunne and Leopold*, 1977). Floodplains do not necessarily identify the CMZ, but they can be useful in defining the limits of

channel migration. The stream CMZ is defined as the lateral extent of likely channel movement over the past 100 years (*WA DNR*, 1999). The CMZ delineates the area over which the channel may occupy based on its dynamic equilibrium characteristics. The CMZ can be identified using historic records, aerial photos, or field verification of paleo-channels or channel features such as braided channels, over-flow channels, progressive meandering, meander cutoffs, oxbows, side channels, or channel avulsions (*Dunne and Leopold*, 1977). Consideration should also be given to the natural or historic levels of LWD found in the stream channel. Streams with abundant LWD often have more active channel migration zones.

Riparian *corridor connectivity* is also an ecologically critical and often under-emphasized component of riparian integrity. Natural riparian corridors in the PNW are nearly continuous throughout the stream-riparian ecosystem (*Naiman and Bilby*, 1998). In addition to buffer width and quality, management of the riparian corridor should focus on minimizing fragmentation of the riparian corridor. Road crossings, utility right-of-ways, and other breaks in the riparian corridor effectively reduce the buffer width to zero and provide a conduit for run-off and pollutants to enter the stream (*May et al*., 1997). Breaks in the riparian corridor should be kept to a minimum and all breaks should be designed for minimal stormwater and other impacts (*Horner and May*, 1999).

Research findings indicate that streams with a high level of riparian integrity have a greater potential for maintaining natural ecological conditions than do streams without a natural riparian corridor (*Horner and May*, 1999). Based on the results of PSL studies, the use of a variable width riparian buffer that will include the structural and functional components of the natural stream-riparian ecosystem, as well as floodplain considerations is strongly recommended. Retention of a wide, continuous riparian zone in forest cover or wetlands has shown to be a management tool with high potential and versatility among those in current use (*Horner and May*, 1999). This practice may also be the simplest to accomplish logistically, the least costly and, accordingly, the most cost-effective. In newly developing areas riparian zones can be isolated from development, along with their associated streams, which are not going to be built over in any event. In already developed landscapes riparian zones are often the least developed and could more easily be bought and put into protective status than upland areas. Riparian retention also fits nicely with other objectives like flood protection and provision of wildlife corridors and open space.

In general, streams with a riparian zone that retains a high level of riparian integrity also have a higher level of ecological integrity than streams in watersheds where riparian integrity is poor (*Horner and May*, 2001). It should be noted that while the retention and enhancement of urban riparian corridors is a sound conservation strategy, it is likely that the mitigating influences of these riparian areas for urbanizing watersheds have limits. The loss of natural landscape (forest and wetlands) cover will at some point cause a significant alteration in the natural hydrologic regime, that will overwhelm any established buffer zone. In short, riparian corridors are not a substitute for watershed land-use management. Protection or rehabilitation of urban riparian corridors is just one of several necessary, but not solely sufficient conditions that must be maintained if urban streams are to retain a natural level of ecosystem structure and function.

Riparian Buffer Zones

The riparian corridor, the riparian community, and the riparian floodplain all are ecologically defined terms that refer to components of the stream-riparian ecosystem. A riparian buffer refers to a strip of land that is jurisdictionally established to mitigate the impacts on the stream system from human activities in the surrounding watershed (*Johnson and Ryba*, 1992). The use of vegetated buffers has become a common practice in our attempts to protect sensitive aquatic resources such as streams and wetlands (*Castelle et al*., 1994). Buffers are also commonly prescribed by critical area ordinances (CAO) to mitigate for the impacts of land-use activities on steep or potentially unstable slopes or other sensitive areas. The scientific principles that form the foundation for delineation of riparian buffers include the following:

- Maintain or restore the freedom of movement of stream channels to move and change within their natural CMZ based on environmental conditions.
- Maintain or restore the connection of the stream to its floodplain, including off-channel habitat, riparian wetlands, and side-channels.
- Allow natural regenerative processes to occur without undo human intervention. Restoration efforts should not conflict with natural processes.
- Protect or enhance biodiversity and habitat complexity within the stream-riparian ecosystem. Recognize and nurture the complexity and diversity of nature. Do not try to mold streams to suit human-based constraints.
- Support or re-establish the longitudinal connections within the stream-riparian corridor. The interactions of headwater areas, mainstem channels, tributaries, and estuaries are critical to the proper functioning of the watershed.

In addition to protecting the natural functions of the riparian corridor outlined in the previous section, riparian buffers can provide the following functions:

- Reduce the encroachment of human land-use activities into the stream-riparian ecosystem.
- Minimize the water quantity and water quality impacts of stormwater run-off and NPS pollution on aquatic ecosystems.
- Reduce property loss or loss of human lives due to high stormflows or flooding events.

Buffers can be fixed or variable in width. Fixed-width buffers are generally the product of political compromise between protecting a natural resource and minimizing the impact on development and private-property rights. Buffers of this type, unless conservatively designed and managed, often fail to support all the ecological functions of the riparian corridor. Variable-width buffers have the potential to be more ecologically based, but are difficult to administer by jurisdictions. It is generally recognized that designing an effective stream-riparian buffer involves the use of five basic criteria (*Johnson and Ryba*, 1992; *Castelle et al*., 1994; *Wenger*, 1999). These are:

- The ecological, cultural, and economic value of the resource being protected.

- The type and intensity of the adjacent land use.
- The vegetative characteristics (vegetation type, diversity, and maturity) of the riparian area and the buffer zone. This is often referred to as riparian quality.
- The condition of the riparian corridor throughout the entire stream system. This addresses the cumulative impact concept of watershed management.
- The stream-riparian functions being supported and the sensitivity of the resources being protected.

As the above criteria indicate, a one-size-fits-all buffer likely will not work. This would argue for a watershed-by-watershed, stream-by-stream, and site-by-site approach. This integrated, hierarchical approach may look to be a daunting and costly task, but it will have to be done if we are to conserve salmonid resources, protect of water quality, and improve quality of life. Again, it must be emphasized that buffers alone are not enough to protect salmonids or water quality. Even the best riparian buffer cannot protect instream habitat if the channel is continuously scoured by high flows caused by run-off from impervious surfaces and routed to the stream by stormwater infrastructure.

In some cases, vegetated filter strips (VFS), primarily of grass, have been used to reduce the impact of agriculture and stormwater run-off on downstream aquatic resources. These VFS or bio-swales may also utilize trees and wetland plants to filter out sediment and pollutants. In general, these filter strips are designed primarily for pollutant removal and do not provide for other critical riparian functions such as LWD recruitment, temperature control, or fish and wildlife habitat.

Impacts of human activities on stream-riparian ecosystems are numerous and highly variable. The effects of land-use activities are often due to multiple stressors and are usually cumulative in their impact (*May et al*., 1997). The characteristics of the stream-riparian ecosystem will also influence the extent and intensity of the human-induced disturbance. Variables such as stream size, location within the watershed, stream gradient, valley configuration, valley side-slope, watershed topography, soil type, riparian vegetation conditions, rainfall patterns, and others all combine to make some stream-riparian ecosystems more or less sensitive to human impacts (*Wenger*, 1999). For example, a stream with an extensive floodplain area will react quite differently than a stream within a deep, steep-walled ravine. So too will streams in watersheds dominated by glacial till soils as compared to those dominated by glacial outwash soils.

Forest management activities within a watershed have been shown to have a significant negative impact of the stream-riparian ecosystem (*Steinblums et al*., 1984; *Bilby*, 1988; *Meehan*, 1991; *NRC*, 1996). Timber harvest and logging roads can directly or indirectly impact the ecological integrity of the stream-riparian ecosystem. Reduced shade, increased fine sediment inputs, and reduced LWD quantity and quality all can result from poor forest management operations. Riparian buffers have been used extensively to reduce the impacts of timber harvest. In fact, much of the research on the effectiveness of forested buffers has focused on mitigation of logging impacts (*Johnson and Ryba*, 1992).

Agricultural activities such as farming and livestock grazing can also have a significant negative impact on stream-riparian ecosystems (*Lowrance et al*., 1984; *Dillaha et al*., 1989; *Meehan*, 1991). The quality of agricultural run-off can significantly affect stream

water quality. The Washington Department of Ecology (WDOE) has identified small farms in floodplain and upland areas of watersheds as a significant source of NPS pollution, including fecal coliform (FC) bacteria from livestock waste, fine sediment from exposed soil, nutrients from fertilizers, and toxic pollutants from pesticides and herbicides. This has been identified as a significant problem in Kitsap County as well (*Kitsap County Health Department*, 1999). Improper grazing practices can also degrade the stream-riparian ecosystem in other ways, including loss of riparian vegetation due to grazing, erosion of streambanks due to livestock access, and increased turbidity from fine sediment inputs. In general, research has indicated that use of proper agricultural BMPs, limiting livestock access to the stream and riparian area using fencing and maintenance of vegetative buffers along the riparian corridor can significantly reduce the impacts of agricultural activities (*Lowrance et al*., 1984; *Lowrance et al*., 1997; *Lowrance et al*., 1998).

Watershed urbanization, which includes rural, suburban, and urban development can also have significant negative impacts on the ecological integrity of the stream-riparian ecosystem (*May et al*., 1997). Little is known about the effectiveness of riparian buffers in mitigating for the cumulative impacts of urbanization, but research indicates that a combination of riparian buffers, land-use controls, and an aggressive stormwater management program may be the best strategy (*Horner and May*, 1999). Due to the diverse nature of development impacts, buffers alone will likely not be enough.

The direct impacts of development on the stream-riparian ecosystem include the following:

- Loss of riparian forest quantity and quality due to encroachment.
- Fragmentation of the riparian corridor due to road and utility crossings.
- A shift in the natural hydrologic regime from subsurface flows (groundwater and interflow) to a surface dominated regime as a result of loss of watershed forest cover and the proliferation of impervious surfaces.
- Loss of canopy interception and evapo-transpiration.
- Degraded water quality due to NPS pollution and stormwater run-off.

The appropriate buffer size will depend on the spatial area necessary to maintain the desired riparian functions and on the combination of land-use activities that are influencing the stream-riparian ecosystem. For example, a wider buffer may be required in situations where high-intensity land-use is found, than in areas of low-intensity land-use. Similarly, all else being equal, a sensitive tributary stream used by salmonids for spawning and rearing may require larger buffers than does a mainstem stream used only as a migration corridor. Of equal importance to buffer size (width and extent of the corridor) is the quality of the riparian area in terms of vegetation type, diversity, physical condition, and maturity. Ideally, the riparian corridor in a developing or developed watershed should mirror that found in the natural ecosystems of that region. Due to the cumulative impacts of past and present land-use, this is often not the case (*May et al*., 1997). Many of our lowland streams have narrow, fragmented riparian corridors that lack the mature coniferous trees, which characterize the few, pristine watersheds that remain. In general, the relatively young, deciduous riparian forests that are common in our

lowland watersheds do not provide all of the functions of mature riparian forests (*May et al*., 1997). The supply of allochthonous organic matter and woody debris provided to the stream, the rain interception capacity of the canopy, and the shade are all different than natural riparian forests.

In short, the quality of riparian buffers we manage should equal that of natural ecosystems. In general, native vegetation is preferred over exotic or landscaped plantings. The exception to this is the use of VFS, usually grass, to treat stormwater or agricultural run-off. These VFS can be quite effective if sheet flow is maintained, the system is not overloaded with sediment, and the soils allow for infiltration (*Karr and Schlosser*, 1977; *Dillaha et al*., 1989; *Osborne and Kovacic*, 1993; *Daniels and Gilliam*, 1996). Upland erosion control, sediment source controls, and proper maintenance are critical to the long-term effectiveness of a VFS (*Dillaha et al*., 1989; *Barling and Moore*, 1994; *Horner*, 1996).

Natural riparian areas in the PNW are composed of a diverse array of coniferous-dominated mature forest, alder-dominated young forest, as well as off-channel and forested wetlands. The linkage between the aquatic and terrestrial ecosystems in the stream-riparian corridor is very strong in the PNW (*Willson et al*., 1998). In managing our watersheds, we should establish conservation and restoration goals that support a properly functioning, natural stream-riparian ecosystem. Natural riparian corridors in the PNW are nearly continuous throughout the stream-riparian ecosystem (*Naiman and Bilby*, 1998). In addition to buffer width and quality, management of the riparian corridor should also focus on minimizing fragmentation. Road crossings, utility right-of-ways, and other breaks in the riparian corridor effectively reduce the buffer width to zero and provide a conduit for run-off and pollutants to enter the stream (*Schueler*, 1995; *May et al*., 1997; *Weller et al*., 1998). Breaks in the riparian corridor should be kept to a minimum.

Riparian zone management should focus not only on buffer widths, but also on corridor connectivity, maturity of vegetation, and species diversity. Management should be approached on a broad landscape scale (watershed-level) with due consideration for other conditions within the watershed as a whole. Based on the findings of this study and current literature, the following guidelines are offered for the design of functionally appropriate urban stream buffers:

- A baseline (minimum) buffer width of 30–50 m (100–150 feet) should provide adequate stream protection in most situations where the buffer is of good quality (mature forest) <u>and</u> the adjacent land-use is not too intense (rural or suburban). The overall target should be maintaining greater than 70% of the total riparian corridor at or above 30 m in width.
- Buffer boundaries must be delineated and monitored frequently for human encroachment. Land owners should be educated on the benefits of buffers and encouraged toward a stewardship role in buffer maintenance. No more than 10% of the riparian corridor should be allowed to become functionally lost due to the encroachment of development (i.e., < 10 m in width).
- The target for riparian buffer quality should be specified as native mature forest. This will almost certainly require active management including tree

plantings, LWD enhancement, and long-term monitoring. A corridor target of mature riparian forest, interspersed with riparian wetlands would seem to be a reasonable long-term goal to ensure adequate LWD recruitment.

- Buffer sizing should be based on the value of the aquatic resource balanced against current buffer conditions, adjacent land-use intensity, inclusion of the active floodplain (100-year) and riparian wetlands, and steep slopes. Buffers of up to 100 m should be considered for especially sensitive or valuable areas. This will require professional judgment and flexible management.
- Buffer sizing should also take into account the upstream condition of the riparian corridor with the goal of attaining a near-continuous riparian corridor. This should include minimizing the number of riparian breaks (< 2/km is recommended) and allowing no untreated stormwater run-off to penetrate the riparian corridor. Most buffers are incapable of dealing with all the stormwater generated in a developing watershed. Therefore, structural BMPs must be employed to treat both the quantity and quality of run-off.

In general, the stream-riparian ecosystems on DoD installations monitored during this study had riparian integrity that ranged from very poor (e.g., Clover Creek on McChord AFB) to nearly pristine (e.g., Cub Creek on NCS Jim Creek). As with watershed land-use, this reflects the conditions found throughout the greater Puget Sound region. Therefore, riparian forest conservation and enhancement needs to be as a high priority on DoD installations as it should be in off-base watersheds.

Invasive Species

The number and quantity of invasive species found in the riparian corridors of DoD creeks was significant, especially along the more disturbed segments (e.g., Clover Creek on McChord AFB and Murray Creek on Fort Lewis). In general, fragmentation and encroachment of the riparian corridor provides pathways for invasive and exotic species, especially plants. Himalayan blackberry (*Rubus discolor*) and reed canary grass (*Phalaris arundinacae)* are the most common invasive species along these streams, and dominate much of the riparian corridor of Clover and Murray creeks. Evergreen (*Rubus laciniatus*) blackberry, Japanese knotweed (*Polygonum cuspidatum*), and climbing nightshade (*Solanum dulcamara*) are generally present throughout each stream corridor, often most abundant in the lower reaches of the stream. Morning glory (*Convolvulus arvensis*), yellow flag iris (*Iris pseudacorus*), and purple loosestrife (*Lythrum salicaria*) are also present in the less disturbed riparian areas along these streams. While many of these invasive plants may provide some beneficial functions to the stream ecosystem (shade, detritus, bank stabilization, etc.), they are not a source of LWD to the stream and also prevent native riparian species from becoming established. A strong invasive plant control program is recommended for all PNW DoD installations.

Channel Form and Streambank Stability

Streambed and streambank instability are some of the most significant problems observed in urbanizing streams in the PSL region (*May et al*., 1997). With the increased surface water dominated hydrology that results from watershed development, streamflows tend to

increase for a given storm event, and the duration of high-flow events also increases (*Booth*, 1991). The resultant higher peak flows and more frequent bankfull, channel-forming events increase streambank erosion, bedload transport, and streambed scour (*Leopold*, 1968). Urbanizing streams tend to over-widen and incise as a result of more frequent bankfull flows (*Dunne and Leopold*, 1978; *Booth*, 1990). This confirms the conclusion that a modified hydrologic regime in these basins has negatively impacted stream channel morphology and has caused excessive streambank erosion and sediment deposition. The lack of LWD and poor riparian condition also contribute to poor streambank conditions in general.

Research in the PSL region indicates that the combination of altered hydrologic regime, loss of instream structure (LWD), and reduction in riparian integrity as a result of basin urbanization, have led to an overall increase in streambank erosion as measured by the streambank stability rating. Stable, vegetated streambanks are a dominant feature of natural, reference stream segments. LWD and roots of riparian trees provide bank protection in natural stream channels (*Bilby and Likens*, 1980). Gradually sloping, vegetated banks and adjacent floodplain areas also provide stability to the active channel margins. In low-to-moderately developed sub-basins, stable streambanks were still the norm, with only a few reaches showing the effects of localized conditions (loss of riparian cover, encroachment of development, residual effects of agriculture, and construction). In general, as sub-basin development increases, streambank stability decreases and bank erosion is more common. This corresponds closely to the shift in basin hydrologic regime as was discussed earlier in this section. This is logical because available stream power is proportional to discharge. As streamflows increase with development, so does the frequency of streambank erosion. Exacerbating the situation is the loss of instream structure (LWD) and channelization, which creates locally severe erosive flow conditions. *Booth and Reinelt* (1993) also noted a consistent loss of channel stability at about 10% basin impervious area. Also noted in the same study (*Booth and Reinelt*, 1993), was a difference in channel size and streambank condition between vegetated and modified streambanks. Obviously, riparian integrity has a significant influence on streambank condition.

The combination of atypically large sediment loads and stream channel enlargement has a profound impact on the longitudinal structure of urban streams. The sequence of pools and riffles that is characteristic of natural streams tends to be degraded into a uniform depth, glide-dominated channel as the gradient and dimensions of the stream adjust to accommodate more frequent, higher flows (*Lisle and Hilton*, 1992). Elevated storm flow and resultant channel enlargement also have a significant impact on instream physical habitat conditions (*Booth*, 1990; *Booth*, 1991; *May et al*., 1997). Washout of LWD is common, as is scouring and removal of salmonid spawning gravels. In addition, fine sediment from streambank erosion and external sources (e.g., construction site run-off) can be deposited on salmonid spawning areas and cause increased egg and embryo mortality (*Chapman*, 1988). In general, the combined impacts of modification of natural stream hydrology and channel morphology result in a loss of physical habitat quantity (both spawning and rearing) and degradation of instream habitat quality (*May et al*., 1997). Streambed scour and fill are natural processes in PNW streams, but excessive scour, aggradation, and streambed instability can have a detrimental effect on instream habitat and biota, especially benthic organisms.

Streambank erosion has been found to affect a large portion of the channels in the developed watersheds of the region (*May et al*., 1997). Artificial streambank protection was also a common feature, especially in highly urbanized streams. Urban streambank reinforcement (rip-rap) can adversely affect salmonid habitat and abundance, especially in small, habitat-limited streams (*Knudsen and Dilley*, 1987). Basin urbanization and loss of riparian vegetation are two of the factors contributing to erosion and instability of streambanks (*Booth*, 1991; *Booth and Reinelt*, 1995; *May et al*., 1997). Besides vegetative cover, other stream corridor characteristics, such as soil type and valley hillslope gradient, also contribute to the potential stability and condition of the streambanks. Riparian vegetation stabilizes streambanks and minimizes streambank erosion. The roots of riparian vegetation and LWD also provide the bulk of this function in the PNW (*Bilby and Likens*, 1980).

In general, most of the streams surveyed during the PNW-DoD stream project showed only minimal signs of channel morphological impact due to high flows or excessive fine sediment deposition. There are a few notable exceptions. Channel conditions for Clover Creek on McChord AFB have been significantly modified from their natural state. In addition to the long runway culvert, almost the entire length of the stream within the base has been ditched and channelized. A majority of the streambank has also been hardened with rip-rap or concrete. The channel has essentially been engineered to accommodate the stormflows from the watershed upstream of the base. This may be hydraulically effective, but there is little ecological value to this configuration. The combination of the runway culvert and the highly altered stream channel is likely a migration barrier for juvenile as well as adult salmonids during high and low flow periods. Salmon are able to migrate during moderate flow conditions. Short of creating a new, natural stream around the runway and flightline, only minor enhancements can be made to the channel to improve ecological function. These include restoration of native riparian vegetation to stabilize streambanks, installation of instream LWD to enhance channel complexity, and retrofit of stormwater run-off controls throughout the watershed (on base and off).

The segment of Jim Creek that flows through the ground-field antenna zone has also been altered from its natural condition. The creek has been straightened and constrained to a relatively narrow CMZ. The streambanks within the ground-field zone have also been armored to reduce erosion and prevent natural meandering. Due to ground-field zone operational restrictions, the riparian corridor has also been cleared of trees. As a result of these measures, there is little instream LWD and channel complexity is low. Because of this, flow energy dissipation is less and stream power is generally greater than it would be under natural channel conditions. This has caused some downstream streambank erosion and LWD washout. The streambed within the ground-field has also been augmented with large rock to serve as energy dissipation material. The channel can be characterized as a cascade. Short of moving the transmitter access road from the floodplain and restoring the natural stream, only minor enhancements can be made to the channel to improve ecological function. The installation of additional roughness elements (LWD and boulders) should be considered in order to provide energy dissipation, enhance instream habitat complexity, and improve salmonid migration. The restoration of riparian vegetation is also an important consideration.

On NSB Bangor, streambank stability ratings for the Devils Hole Creek indicate streambank erosion due to frequent excessively high stormflows is common. All but a few segments in the developed portion of the watershed were dominated by eroding or armored streambanks. Assessed segments of the creek with a high percentage of forested riparian zone reaches often had more stable banks. Fine sediment deposition was also noted as a recurring problem within the Devils Hole Stream system. Soils in the Devils Hole watershed have a high potential for erosion and rely heavily on native vegetation cover for protection. Therefore, the need for riparian restoration (and invasive species control) and stormwater management is critical.

Large Woody Debris

Few segments in the assessed DoD streams had LWD frequencies above the low end of published ranges for natural conditions in the PNW (low-end range: 200–400 pieces/km in accordance with NMFS guidelines). In general, small, natural stream channels in the PNW tend to contain an abundance of LWD (in many cases in excess of 600 pieces/km). Only the lower-most segments of Jim Creek, Cub Creek, and Muck Creek had LWD frequencies greater than 150 pieces/km. The importance of LWD and its functional role in streams in urbanizing watersheds of the PSL is very much the same as it is for streams draining natural forests in other PNW ecoregions. LWD performs critical functions in forested lowland streams, including flow energy dissipation, streambank protection, streambed stabilization, sediment storage, and providing instream cover and habitat diversity (*Keller and Swanson*, 1979; *Bilby*, 1984; *Harmon et al*., 1986; *Bisson et al*., 1987; *Gregory et al*., 1991). Research has shown that LWD in low-gradient pool-riffle or plane-bed streams found in the PNW has the significant ecological influence (*Bilby and Ward*, 1989 and 1991; *Montgomery et al*., 1995; *May et al*., 1997).

Natural frequencies and volumes of LWD were only found in assessed stream-segments that contained a wide, mature and coniferous dominated forest component within the riparian zone, which may function as a source of LWD and as a buffer to prevent LWD removal by area residents. Numerous studies have found LWD recruitment potential depends heavily on riparian corridor quality and extent (*Murphy and Koski*, 1989; *Van Sickle and Gregory*, 1990; *Johnson and Ryba*, 1992; *Fetherston et al*., 1995; *Rot et al*., 2000). It is the general consensus of most scientists that nearly all LWD is derived from the riparian zone within one site potential tree height (SPTH) of the active stream channel (*FEMAT*, 1993). Having a fully forested riparian corridor does not, however, ensure natural levels of instream LWD. This emphasizes that numerous mechanisms of LWD loss are operating in an urbanized stream ecosystem, including washout due to high storm flows, and shows the importance of maintaining wide and continuous riparian buffers around sensitive ecosystems such as streams and wetlands.

Even more significant than the decreased LWD volume and frequency in DoD streams was the lack of larger key pieces of LWD within these systems. Large pieces of LWD are particularly important for anchoring debris jams that can have significant effects on instream habitat (*Maser et al*., 1988), and pool size is also influenced by LWD size (*Naiman and Bilby*, 1998). Riparian integrity, including riparian buffer width and the various aspects of riparian quality, such as stand-age and species composition, is especially influential on LWD size (*May et al*., 1997). LWD-influenced biological

changes typically follow the physical changes (*Harmon et al*., 1986). The physically induced biological influences of LWD are substantial. Fish populations have been shown to decline rapidly following LWD removal (*Bryant,* 1983; *Hicks et al*., 1991; *May et al*., 1997).

One of the largest contributing factors to the loss of instream LWD in urbanizing watersheds, such as are common in developing DoD installations, is the loss of riparian integrity (*May et al*., 1997). Riparian integrity includes the extent (width) of the riparian zone, the continuity of the riparian corridor, and the quality of the riparian vegetation, including forest stand age and tree species composition (*May et al*., 1997). Comparison of riparian buffer and LWD parameters shows a strong quantitative and qualitative relationship. Both LWD frequency (#/km) and total volume (m^3/km) are substantially influenced by riparian buffer width. The inverse is true for riparian encroachment. If more than 10% of the riparian buffer is functionally impaired (< 10 m in width), then LWD will probably not exist in significant quantities within the stream system (*May et al*., 1997). Riparian quality (as measured by the fraction of the buffer in a natural condition) also strongly influenced LWD quantity. The bottom line is that functionally significant levels of LWD will probably not exist unless the riparian corridor is maintained in a predominantly natural condition (*Horner and May*, 1999).

The loss and/or removal of LWD, along with the increased flows due to basin urbanization, can have a feedback effect on the remaining in-channel LWD causing further losses and continued unraveling of the natural ecosystem. The relative significance of high flows and decreased LWD are often difficult to distinguish between. The lack of LWD in urbanizing streams in the PSL also leads to degradation of instream physical conditions (*Booth*, 1991; *May et al*., 1997; *Larsen*, 1999). Channels experience greater scour, erosion, and lateral instability; the flux of sediment is greater and more closely tied to individual high-flow storm events; and the habitat diversity of natural streams is replaced by a uniform channel profile and cross-section (glide-dominant). Many of these effects are also a product of the increased discharges that normally accompany urbanization, but the loss of stream power dissipation by LWD is certainly significant (*Keller and Swanson*, 1979; *Bisson et al*., 1987; *Ralph et al*., 1994). The mechanisms by which LWD is lost from urban stream channels are similar to streams affected by timber harvest, but in general, are more pervasive and on-going.

Probably the most widespread and most difficult to detect removal mechanism in urban streams is human removal. This is also a loss mechanism, which is unique to urban streams. After timber harvest operations there is little human contact with the riparian buffer, but in an urban setting there can be near-continuous human intervention. This affects not just inchannel LWD-related processes, but also LWD recruitment from the riparian zone. Local flood-control concerns have also driven removal of some inchannel LWD. Mobilized LWD often becomes lodged in culverts or jammed under bridges at road crossings, necessitating removal by surface-water utility crews. Culverts are especially problematic with respect to LWD redistribution in that natural redistribution of LWD downstream is nearly impossible if culverts are in place. Landowners also may remove instream obstructions for drainage or flood-control considerations. Removal of riparian trees for firewood and to prevent wind-fall home damage are also factors of concern. Due to the encroachment of development, this instream removal problem is

further exacerbated by removal of LWD from riparian areas and/or the loss of potential LWD from riparian forests themselves. Removal of LWD for aesthetic reasons is also a major consideration. *Gregory and Davis* (1993) found that people had a strong preference for natural streams but channels without instream LWD were preferred to those with debris. Despite the ecological advantages of LWD, it seems that people find streams with natural LWD messy. It was also found that most people tend to prefer riparian areas that consist of natural but not wild vegetation (*Mosley*, 1989; *House and Sangster*, 1991; *Gregory and Davis*, 1993).

Washout is also a major mechanism for LWD loss from urban streams. As has been discussed, watershed development leads to an increase in peak discharge (*Hollis*, 1975). The duration of flood flow events also may increase by an order of magnitude or more (*Booth*, 1991). The frequency of dominant discharges (major transport events) can also increase dramatically (*Booth*, 1991). In addition to increasing sediment transport competence, these flows are also capable of moving all but the largest of LWD. The change in hydrologic regime also tends to expand the channel cross-sectional profile through lateral expansion and/or incision (Booth, 1990). This may expose more individual LWD pieces to high flows, as well as undermine and destabilize previously anchored or buried LWD, increasing the chance of movement and/or washout. Bedload stored behind LWD also becomes susceptible to transport, increasing sedimentation and scour of the downstream channel (*Bilby and Likens*, 1980; *Bilby*, 1984; *Lisle*, 1987).

Stranding is a related mechanism of LWD loss in urban streams and is caused by the same high flows as washout. Due to the combined effects of channel enlargement and incision, LWD may become beached outside the active stream channel flow. Primarily as a result of the increased sediment transport competence of urban streams and lack of bedrock gradient control in the PSL, down-cutting (incision) of the streambed often results, especially in small tributary streams. Therefore, LWD can become suspended above the streambed and is ineffectual in providing any flow resistance. This further loss of flow resistance typically accelerates the incision process and may result in catastrophic LWD washout as well. Channel widening in urban streams can also leave LWD high-and-dry on the channel margins. Both of these conditions were observed in the DoD survey streams.

While all these LWD loss mechanisms are sometimes assumed to be gradual and reversible in nature, the experiences of forest resource managers would indicate otherwise. *Bilby and Ward* (1991) found that human activity in the riparian zone led to rapid and generally severe changes in stream channel structure and processes. Observations of urban streams in the PSL confirm this basic unraveling of the system (*May et al.*, 1997). The rapid decline in instream habitat quality and quantity that accompanies the onset of basin development supports this contention. The fact that over 100 years is required for a mature, natural riparian forest to be re-established after it is removed (*Grette*, 1985) is even more reason for protection and nurturing of wide riparian corridors surrounding DoD streams.

Salmonid Migration Barriers

Man-made barriers to salmonid migration were a significant problem on several DoD streams surveyed during this project. The fish ladders on Devils Hole Creek (NSB

Bangor) and Cub Creek (NCS Jim Creek) were found to be at least partial barriers to upstream migration by some species of adult salmonids. The outlet spillway on Cattail Creek (NSB Bangor) is a complete barrier to anadromous salmonids. These structures should be removed or replaced with properly designed fishways. Several culverts on upper Devils Hole Creek (NSB Bangor) were also identified as migration barriers for both adult and juvenile salmonids. These culverts should be replaced with bridges or bottomless culverts of the proper size. This should be done at the earliest opportunity. Restricting salmonid access to habitat, especially high quality habitat (e.g., upper Cub Creek on NCS Jim Creek), occurs far to often as a result of man-made barriers. Opening this habitat to all native salmonid species should be one of the top priorities of DoD natural resource managers. The removal of the Cub Creek dam or the installation of a functional fish ladder should be one of the these high-priority projects.

Instream Salmonid Habitat

Adequate high-quality rearing habitat is generally recognized as one of the critical limiting factors influencing salmonid productivity. This is especially true of winter rearing habitat (high-flow refuge and cover) for juvenile coho salmon (*Brown and McMahon*, 1987; *Reeves et al*., 1989; *Nickelson et al*., 1992). LWD is probably the key component of salmonid rearing habitat in small streams in the PNW and is critical to over-winter survival of juvenile coho salmon (*Bustard and Narver*, 1975; *Brown and McMahon*, 1987; *McMahon and Hartman*, 1989; *Nickelson et al*., 1992). LWD not only provides habitat structure and high-flow refuge, it also is a major form of instream cover for young fish. Coho, in particular, have a strong preference for pools with structurally complex (LWD) micro-habitat (*McMahon and Hartman*, 1989; *Shirvell*, 1990). Cutthroat trout appear to have similar preferences for rearing habitat as coho, but may be more adaptable to less than ideal conditions (*Heggenes et al*., 1991).

The quantity and quality of pool habitat in PSL streams mainly due to cumulative effects of urbanization. This includes changes in the natural hydrologic regime, increased fine sediment loading from streambank erosion and stormwater run-off, and reduced LWD recruitment due to loss of riparian integrity. Stream segments with greater than 40% of their surface area as pool habitat were found only in reaches with relatively undisturbed, natural riparian corridors. In general, most of the DoD streams with pool habitat within the NMFS target range (40–60%) were in watersheds with low levels of landscape alteration. This seems to indicate that even where sub-watershed development is fairly high in these watersheds, salmonid habitat may still be maintained by preserving extensive riparian buffers. However, several stream segments with natural riparian conditions had less than optimum pool habitat, again demonstrating that instream habitat is a function of multiple external variables, in addition to riparian integrity.

The linkage between riparian conditions and instream habitat hinges on many variables, an important one being LWD recruitment. Pool frequency and depth, surface area, and cover-quality are typically directly related to LWD quantity and quality (*Andrus et al*., 1988; *Robison and Beschta*, 1990; *Ralph et al*., 1994). In general, the pervasive nature of watershed development has caused degradation of instream habitat, particularly rearing habitat (*Scott et al*., 1986; *Imhof et al*., 1991; *Lucchetti and Fuerstenberg*, 1993; *May et al*., 1997).

In general, quantity of riffle (spawning) habitat was also below the optimum 40–50% level in most of the assessed DoD stream segments. Riffle quality was below optimum in several DoD streams (i.e., Devils Hole Creek, Murray Creek, and Clover Creek), primarily due to elevated fine sediment levels and high levels of substrata embeddedness. The lowest quality riffles were generally in the lower gradient response reaches of these creeks, where water velocities decrease and suspended sediments are deposited.

A general shift in habitat dominance from balanced pool-riffle morphology to a glide-dominated habitat structure was also detected from the assessment data. Glides are intermediate habitat units, which have some of the characteristics of both pools and riffles but provide little of the functional habitat capabilities of either. While relatively deep and slow during baseflow conditions like pools, glides provide little cover or flow refuge during peak-flow periods, thus provide generally poor rearing or refugia habitat. In addition, glides also provide generally poor spawning habitat due to their lack of hyporheic flow and susceptibility to streambed armoring (*May et al*., 1997). Several DoD streams surveyed during this study (i.e., Clover Creek on McChord AFB, upper Muck Creek on Fort Lewis, and Murray Creek on Fort Lewis) had significant fractions of their overall instream habitat in glides. This shift to glide habitat may be due to the lack of a significant quantity of pool forming LWD in the assessed streams. *Montgomery and Buffington* (1997) found that forced pool-riffle reach morphology changes to glide dominated plane-bed morphology with the loss of instream LWD (*Montgomery et al*., 1999). Instream LWD is the key to channel diversity and complexity in PSL streams.

Habitat Quality Index

The HQI is intended to be a simplified descriptor of habitat quality for a stream segment, mainly for comparison purposes during the stream assessment process. This index uses the major components of high quality instream habitat to define the optimum condition (based on the NMFS MPI criteria and published values for undisturbed streams). Only elements that were directly a part of instream habitat quality were included in the HQI. For example, LWD was included, however, riparian vegetation was not. In addition, wetlands were not included in the index, because wetland extent was not quantified and wetland quality was not assessed. This is not to say that wetlands are not an important habitat feature. Natural floodplains and riparian wetlands are critical components of a properly functioning aquatic ecosystem (*Naiman and Bilby*, 1998). Riparian wetlands serve many important ecological functions in the lowland stream ecosystem including stormwater storage, sediment filtering, and NPS pollutant uptake (*Reinelt and Horner*, 1995). Protection and enhancement of wetland areas associated with PSL streams should be a high priority.

The HQI evaluation of habitat quality may be useful for identifying areas for further investigation. Habitat quality ratings may suggest actions to consider for future planning, or restoration projects. Segments rated “low” or “medium” may benefit from restoration activities. Segments rated “high” quality habitat by the HQI may be good candidates for acquisition or protection. Because many aspects of good quality stream ecosystems have not been included in this index, and the provisional and preliminary stage of the index development, this HQI should not be used as the sole source of habitat quality information for decision-making. In general, the HQI ratings appear to reflect the land

use of adjacent, local areas. This suggests that "local" conditions such as riparian integrity probably have as much influence on instream conditions as landscape scale factors such as watershed land-use.

CONCLUSIONS AND RECOMMENDATIONS

Site-specific recommendations for each DoD installation and each stream are included in the individual stream assessment sections. This section provides more broad guidance for DoD natural resource managers.

Processes occurring within the stream, in the surrounding riparian zone, and within the watershed all contribute to the creation and maintenance of instream habitat structure. These processes must be examined in order to evaluate factors that contribute to degraded habitat quality. The data from the habitat assessments described in this document indicate that many segments of DoD Creeks lack the complex habitat structure that is important for sustaining a long-term, diverse salmonid population. Inadequate pool and riffle habitat in PSL streams is likely a result of the cumulative effects of the interruption of numerous natural processes such as sediment transport, large woody debris recruitment, and the basin-wide hydrologic regime that interact to create these habitats. Restoration and conservation planning efforts need to assess, and take into account the processes that create instream habitat structure.

Results of this study and others in the PSL region demonstrate that retention of a wide, nearly continuous riparian buffer in native vegetation has greater and more flexible potential than other options to uphold biological integrity when development increases. In newly developing areas riparian zones can be isolated from development, along with their associated streams. In developed landscapes riparian zones are often more lightly developed than upland areas, and could more easily be purchased and placed into protective status. Riparian retention fits nicely with other objectives, like flood protection and provision of wildlife corridors and open space. Instream habitat would benefit most from the securing and protecting of existing high quality riparian buffers, enhancing or restoring degraded, but undeveloped areas, and protecting developed riparian zones and upgrading the integrity of the buffer with planting native (especially conifers) and removing invasive plants. General forest retention throughout watersheds offers important potential mitigation benefits (*Horner and May*, 1999). It should be a high priority, especially for managing growth of undeveloped and lightly developed watersheds, in connection with impervious surface limitation and riparian protection efforts. Most likely, the potential benefits shown for riparian and forest retention could be compounded by pursuing both in concert.

The foundation of any effective environmental management effort must be goals developed with firm knowledge of what the ecosystem is capable of under varying circumstances, and what it needs to attain the desired level of ecological integrity. Goals should be stated in concrete and measurable terms. Management actions must be prescribed with reference to individual ecosystem conditions. This study should provide a solid baseline for future management decisions regarding DoD streams in the PNW. In addition to military operational requirements, the foundation for DoD land-use decisions should include ecological considerations. The Ecological Society of America (*ESA*, 2000) has published a set of basic guidelines for land-use that should be applied to watershed management. These guideline include the following:

1. Examine the impacts of local decisions in a regional context.

2. Plan for long-term change and unexpected events.
3. Preserve rare landscape elements, critical habitats, and associated species.
4. Avoid land uses that deplete natural resources over a broad area.
5. Retain large contiguous or connected areas that contain critical habitats.
6. Minimize the introduction and spread of nonnative species.
7. Avoid or compensate for effects of development on ecological processes.
8. Implement land-use and management practices that are compatible with the natural potential of the area.

Watershed and Stream Management

An important goal of DoD watershed management should be the protection of aquatic resources. In the PNW the critical resource is most often the native salmonid community. This should be a main focus of any conservation or restoration efforts involving streams and wetlands. This resource protection strategy involves an interdisciplinary, multifaceted approach to resource protection. This approach includes the following key elements:

1. Watershed-based land-use planning.
2. Reducing impervious surface area.
3. Limiting erosion during construction activities.
4. Treating stormwater run-off for both quantity and quality.
5. Preserving high-quality stream ecosystems.
6. Protecting sensitive areas.
7. Establishing ecologically based riparian buffers.
8. Monitoring, education, and public outreach.
9. Establishing a stream rehabilitation program.

Based on the results of this research on DoD installations and previous research into the cumulative effects of urbanization, there appears to be a set of necessary, but not sufficient conditions to maintain stream quality in the PSL eco-region. Each of these environmental factors by themselves are not adequate to ensure ecological integrity, but as a whole are essential ingredients to achieve that state. Stream ecosystems are not governed by a set of absolute parameters, but are dynamic and complex systems. In reality, we cannot manage streams, but instead should work more as stewards to maintain natural high stream quality. First of all, <u>preservation and protection of high-quality resources should be a priority</u>. In addition, rehabilitation and enhancement of aquatic resources will almost certainly be required in all but the most pristine watersheds.

Based on current best available science for the PNW, the following watershed management lessons learned are presented:

- Current research indicates that there is an immediate and rapid decline in ecological integrity with the onset of urbanization, which continues as the development process progresses.
- We must understand that we cannot manage nature, but instead should focus on managing human activities within the watershed in support of maintaining ecological integrity (the main goal of the CWA).
- In general, ecosystems become more fragile and susceptible to problems the more we alter the natural system. We should not seek to restore ecosystems to a completely natural state (this is not practical), but we need to learn how to coexist with nature such that these systems are ecologically sustainable with a human presence included.
- We need to assess our aquatic resources on a watershed basis because they are a direct reflection of what is happening in the surrounding landscape.
- We must maintain a big-picture view of the watershed and not get locked in on one issue (i.e., multi-species salmon recovery plans not just "listed" fish).
- There are limits to our understanding of aquatic ecosystem (imperfect science) and associated risks to any actions based on our current level of knowledge. However, we should follow the science, wherever it leads. We should be open and willing to do whatever it takes to get the job done right (adaptive management).
- Cultural values are at least as important as science in the overall watershed scheme.
- Understanding the structure, functions, and processes of aquatic ecosystems is the key to successful watershed management.
- We should plan for disturbance. Natural aquatic ecosystems are continuously changing (dynamic equilibrium).
- Minimize watershed imperviousness cover.
- No development should be allowed within the active floodplain (this is common sense as well as scientifically justified).
- Maintaining or restoring the natural hydrologic (disturbance) regime is one of the single most important factors in an urban watershed management effort.
- Preservation and re-establishment of natural forest cover is an essential element of retaining or restoring the natural hydrology of the watershed. A high level of natural, mature, and dominantly coniferous forest cover is scientifically supported.
- The preservation and/or restoration of a wide, mature, and nearly continuous riparian forest around <u>all</u> streams (seasonal and perennial) is also essential to the natural structure and function of stream and wetland ecosystems.

- Limit encroachment of the riparian buffer zone through education and enforcement.
- Protect, enhance, or re-establish headwater wetlands and off-channel riparian wetland habitat as natural stormwater storage areas and aquatic biota refuges.
- Nearly all PNW streams, even in undeveloped watersheds, lack sufficient LWD, the principle structural component of PNW stream ecosystems. Therefore, some instream habitat enhancement or rehabilitation will be necessary in almost every watershed. These projects should not be undertaken without first ensuring a natural hydrologic regime exists or most will be doomed to failure.
- Maintain stream system drainage density that mimics pre-development conditions. This will require reducing the number of stream-crossings (primarily roads) and eliminating uncontrolled stormwater outfalls.
- Culverts should be replaced by bridges wherever practical or, as a minimum, arched-culverts with natural streambed bottoms should be used.
- Current stormwater management practices have been largely ineffective in protecting stream ecosystems from the cumulative effects of urbanization. Assimilative capabilities of natural forests and their soil structure cannot be replaced with engineered stormwater retention/detention facilities (ponds) without suffering some instream degradation due to (mainly) flow-related impacts.
- We must significantly reduce the impervious surface area (and partially pervious areas, such as lawns) within our watersheds. A great majority of our impervious surfaces are transportation related, so we should concentrate on those first, but should also make an effort to infiltrate roof-top run-off whenever possible.
- We should adopt a goal of zero effective imperviousness (i.e., no impervious surfaces directly connected to the natural drainage network without stormwater quantity controls and quality treatment).
- We need to make some fundamental changes in the way we develop our watershed areas for residential, commercial, and industrial land-uses. Low-impact or conservation design techniques (such as clustering) should be encouraged and supported by local government.
- The use of natural (non-structural) BMPs should be our primary tool for stormwater management. Bio-filtration, bio-retention, and infiltration should be the BMPs of choice for instream habitat protection. Structural BMPs should be regionalized as much as possible and should focus on flooding prevention, human safety, and property protection.
- Innovative stormwater treatment BMPs should be utilized to maintain water quality, especially in higher developed watersheds. Stormwater "hot-spot"

treatment (on-site) should be a major focus of commercial and industrial areas.

Watershed and Stream Assessment

Methods used for assessing stream ecological integrity are continually refined as new information about parameters as indicators of habitat quality, accuracy and precision of methods, and resource management needs becomes available. As a result of the data analysis from these assessments, the following changes to the assessment methods are under consideration:

- Until a better set of criteria are developed based on best available science, the NMFS MPI should be used to assess where streams are in relation to PFC goals.
- Adopt a set of holistic assessment protocols for DoD streams in the PSL region, including standardized biological sampling (B-IBI), instream habitat assessment (TFW), and chemical water quality monitoring.
- Under low-to-moderate basin development, use chemical water quality monitoring sparingly (i.e., only if a chemical pollutant is suspected or in situations where biological monitoring indicates a problem). For highly urbanized watersheds, stream and stormwater sampling should be more frequent but should still be focused on specific constituents of concern.
- It is strongly recommended that all DoD installations develop the capability to conduct watershed assessment and landscape analysis using GIS and remote-sensing technology.
- The RQI was difficult to apply in a manner that was consistent between field technicians. One of the important pieces of information that is incorporated into the RQI scoring is embeddedness. In the future direct measurement of spawning gravel composition using standard methods (e.g., Wolman pebble-counts and/or substrate sieve analysis) should be used.
- Altered hydrology is one of the effects of development on stream ecosystems. Therefore, long-term monitoring of the hydrologic regime should be instituted on all DoD streams.
- Assessment of fine sediment deposition and examination of spawning gravel scour would help determine the extent of harm done to salmonid redds by the cumulative effects of human activities in the watershed.
- Further testing and refinement of the HQI is also recommended to improve this assessment tool.
- The complexity and diversity of salmonid life cycles and stream ecosystems, along with our limited understanding of them, should engender caution in proposing any simple solutions to reverse the cumulative effects of development in DoD streams.

Watershed and Stream Restoration

Most urban streams in the Puget Sound region of the PNW (including many streams on DoD installations) have been altered and no longer resemble their natural state. Efforts to restore urban streams are based on good intentions, but the process for selecting rehabilitation sites often lacks critical scientific information necessary to ensure that the most appropriate sites are chosen, that rehabilitation approaches are appropriate, and that project objectives will actually be met. A recently completed study by the University of Washington, Center for Urban Water Resources Management (UW-CUWRM) offers a strategy for more effective stream rehabilitation (*Booth et al*., 2001). Any human action that alters critical components of a stream system has the potential to degrade the conditions within the stream. Any given level of watershed urbanization influences the hydrologic regime of different streams differently, due to the unique characteristics of that watershed (e.g., geology, soils, topography, channel network) and because of interactions of flow with other stream features. No single assessment index (such as the amount of impervious area in the watershed) can adequately predict changes instream conditions.

Rehabilitation, even with the best analysis and effort, will not produce the same ecological results in every stream, because even a rehabilitated stream will not be the same in every watershed or interact with other environmental factors in the same way. The multiple effects of urban development on stream systems make rehabilitation progressively more difficult in more urban watersheds. Because of this, rehabilitation projects are most likely to be successful in watersheds with relatively low levels of development that display paradoxically poor ecological conditions. Rehabilitation is least likely to produce improvements in highly developed watersheds. This is based on the fact that neither this study nor other previous studies in the Pacific Northwest (or elsewhere in the country) have found very good ecological conditions in highly urbanized watersheds.

Based on these observations, the following strategy and recommendations for effective stream rehabilitation are offered:

1. Recognize and preserve high-quality, low-development watershed areas. Conservation of remaining productive watersheds should be a high priority in regional ecosystem recovery efforts. These areas not only provide refugia areas for salmon and other wildlife, but also serve as potential sources of recolonization populations for nearby degraded watersheds that are targeted for restoration efforts.
2. Systematically and comprehensively evaluate stream conditions in areas of low to moderate development. This will serve to identify key stressors, as well as quantifying the current condition of the watershed and stream ecosystem. This is a critical first step in the recovery process. These results can then be compared to reference conditions to establish the critical pathways to re-establishing PFC.
3. Aggressively rehabilitate streams in watersheds of low to moderate development, where recovery of ecosystem elements and processes is possible and sources of degradation are easier to identify and correct. These watersheds

will also benefit most from the application of low impact development (LID) principles for new development or redevelopment projects (Appendix O).

4. Rehabilitate selected areas of urban watersheds with a moderate to high level of development. Complete recovery is not feasible in these systems, but well-selected efforts may yield direct improvement, particularly on protected public lands or on private property where landowners are motivated through incentive programs or conservation easements. Develop a long-term goal of mimicking the full range of natural hydrology and processes rather than simply addressing symptoms. Structural stormwater BMPs have a place in watershed protection efforts, especially in moderate to highly developed watersheds (Appendix O).
5. Improve the most degraded streams by first analyzing the acute cause(s) of degradation, recognizing that the potential for full ecological restoration is minimal. These areas have value more as public education areas than as naturally functioning ecosystems. The value of these areas should not be discounted because they are not highly productive and diverse ecosystems. In the most highly developed watersheds, community outreach is crucial to the success of rehabilitation efforts. This intrinsic value must be tempered with a realistic expectation of the limited ecological success possible in most of these highly degraded systems. Develop approaches to address the unanticipated consequences of human actions on streams in the name of backyard improvements. Regional and national efforts now fall short in this regard.
6. Localized patches of healthy riparian corridor are effective in maintaining biological integrity, but that effectiveness varies with basin-wide urbanization. Where overall basin development is low to moderate, natural riparian corridors can maintain or improve biological conditions, but in highly urban watersheds healthy riparian corridors alone cannot protect stream ecological integrity. Conserving and enhancing riparian integrity in watersheds of low-to-moderate development level should be a high priority in regional recovery efforts.

Stormwater Management

In general, conventional (structural) stormwater BMPs have an appropriate place in urban water resources management but fall far short of supplying all needs, in contrast to thinking prevalent in most stormwater management programs. It appears that these BMPs have their most potential for benefit at the medium and higher urbanization levels, where they seem to have some positive effect on fish as well as invertebrates (*Horner and May*, 1999). While studies have shown the benefits of structural BMPs in chemical water quality treatment, the evidence is that they offer little flexibility to increase urbanization and still have the best overall ecological integrity in relatively pristine cases, unless exceptionally large numbers of, presumably, high quality BMPs were to be installed. However, as yet, this scenario has not been verified in watershed research. With additional investigation of BMP mitigation pending, little on a specific level can be said about the overall effectiveness of newer BMP quality standards. However, it can be concluded that a mitigation strategy that relies solely on structural BMPs will not

maintain natural levels of ecological integrity. More certain of success, though, would be to limit severely the installation of impervious surfaces and rely to the greatest degree possible on non-structural BMPs that retain natural soil and vegetation cover. In addition to riparian forest conservation, general forest retention throughout watersheds has also been shown to offer important potential mitigation benefits (*Horner and May*, 1999). Forest retention should be a high priority especially in managing the growth of undeveloped and lightly developed watersheds, in connection with impervious surface limitation and riparian protection efforts. Most likely, the potential benefits shown for riparian and forest retention could be compounded by pursuing both in concert. Full coverage of otherwise unmitigated development with structural BMPs should be specified after all possible use of non-structural techniques. Low impact development is an evolving area that shows much promise for stormwater management.

Low Impact Development

Low Impact Development (LID) is a new approach to site planning and design that has an objective of preserving watershed hydrologic functions while reducing construction and long-term maintenance costs for properties. This approach is quite different from conventional-end-of-pipe stormwater management. LID uses a combination of conservation practices and small-scale stormwater management controls that distributed evenly throughout the development to address stormwater objectives. The goal of this guide is to help developers, designers, and builders evaluate the potential of a site for development as an LID project by introducing the main principles of LID and some common planning and design approaches.

Low impact site design is an approach to development that incorporates conservation of natural resources into the land development process. The goal is to design a site such that we protect natural areas, utilize natural site features for stormwater treatment, and create natural amenities that enhance the livability of the development for residents or workers. These principles can be used for residential and commercial developments.

A watershed approach to land use is desirable for a number of fairly obvious and well-documented reasons. A watershed approach allows for recognition of where development should and should not occur. In addition, it allows for management of the cumulative impacts of development on natural resources.

Using the so-called conservation design approach (*Arendt*, 1996) to site layout we integrate conservation of natural areas (often referred to as shared open-space) into the overall site development plan. This is typically done in a density-neutral manner. By this we mean that the overall number of homes is the same as would be permitted in a conventional development if all land were considered buildable. In some cases a density-bonus (more dwelling units per area) may be desirable to provide an incentive for the developer to conserve more natural area. Obviously, this will require the use of clustering (smaller lot sizes and higher density) to preserve the natural areas while allowing construction of the desired number of homes. In most cases this flexibility of zoning density is not currently built into our regulations, although many jurisdictions have some type of cluster development ordinances.

The identification of conservation areas is typically done in two steps (*Arendt*, 1996). The first task is to delineate primary conservation areas. These are natural areas that require protection based on jurisdiction regulations (sensitive area ordinances) or other legal or safety related requirements. Primary conservation areas include wetlands, stream-riparian corridors, floodplains, steep slopes, or critical wildlife habitat. Next, secondary conservation areas are delineated. Secondary conservation areas could include blocks of mature forest, greenways, farmland, historical or cultural sites, recreational areas, and other areas that are deemed to be worthy of protection. The designation of secondary conservation areas should be based on a value judgment of the community. In addition to the obvious ecological benefits, there are social, economic, and recreational advantages to this type of site design. In general, the infrastructure costs for cluster developments tend to be lower and stormwater related costs are also significantly lower due to less impervious area creating less run-off and the use of natural areas for stormwater treatment reduces the need for structural BMP's. The accessibility to natural areas for passive or active recreation is certainly also a plus. The resale value of homes in these open-space developments also tends to be higher (*Arendt*, 1996).

After conservation areas are delineated, then roads, utilities, and lots can be laid out in the remaining buildable area. It is important to note that creative legal solutions will also be required to make this process work. Existing property lines will require the use of conservation easements, transfer of development rights, and other methods to facilitate more flexibility in land use and site design. During the site design phase, the specific low-impact development techniques should be applied. These BMP's will be discussed below.

Zoning regulations should not specify lot size, but should only regulate development density, allowing more flexibility in site design. In addition, mixed land use should be allowed to encourage less dependence on the automobile. The use of clustering should also be encouraged as a means of reducing the development footprint and imperviousness. The conservation of open space should be a high priority. In that roads are a major portion of the impervious surface area in most developments, road width and parking regulations should be amended to allow more flexibility in design (and the use of pervious pavements) to reduce overall imperviousness.

Conservation design is based on preserving the natural features and character of the land. Site plan components include:

- Forest conservation
- Habitat conservation
- Preservation of wildlife corridors,
- Protection of critical areas such as steep slopes, wetlands, and stream corridors
- Agriculture and open space preservation
- Preservation of permeable, native soils

During the initial phase of development, site disturbance should be minimized and erosion control BMP's should be utilized to reduce the impact of construction on

surrounding natural resources. In the PNW, natural forest cover, including understory vegetation and the characteristic, forest duff upper soil layer maintains a sub-surface flow dominated hydrologic regime. If the forest or the absorbent forest duff soil are disturbed or removed, the natural hydrologic processes are altered and surface run-off will increase significantly.

If new development is to achieve a goal of zero-run-off (maintaining the natural hydrologic regime), forest cover and the forest duff layer must be retained over much of the proposed development site. Overall site disturbance should be minimized. In addition, soil compaction should be minimized. Research indicates that soil compaction and the resultant loss of permeability is a significant problem in developed watersheds. This soil compaction can significantly increase the imperviousness of turf (lawn) or landscaped areas.

During construction, surface erosion of exposed soil is a major concern. The sediment load created during the construction phase of development can be significant unless aggressive erosion control measures are taken. In addition, limitations on land clearing, requirements for phased land-clearing, and seasonal restrictions on construction should be instituted for erosion control. The goal should be to retain all soil on site and to achieve zero run-off during the construction phase. Sediment levels in streams, lakes, and wetlands downstream of construction projects should be closely monitored for impacts on spawning habitat. High sediment levels and fine sediment deposition can significantly degrade instream spawning/incubating habitat for salmonids and increase mortality of the egg/alevin life-stage.

The goal is to minimize impacts to the drainage characteristics of the land. Many construction impacts cannot be mitigated or may be extremely expensive and prohibitive. Some common techniques are:

- Minimize clearing
- Minimize mass grading
- Use alternative paving surfaces
- Reforestation
- Disconnect impervious areas
- Reduce amount and size of stormwater infrastructure (pipes, curbs, and gutters)

Under the LID principles, SWM should be integrated into the development process and not be considered an after the fact detail. More importantly, SWM must be viewed from a conservation perspective and not be treated as mitigation. There is solid evidence that the current mitigation-based strategy that relies heavily on structural stormwater BMPs has not been effective in protecting the ecological integrity of PSL streams (*Horner and May*, 1999). For SWM to be effective, it must be integrated into the site design process from the very beginning. Prevention is the key. This holds for water quality (source-controls) as well as water quantity (surface run-off) issues.

Land-use planning and SWM should be coordinated on a sub-watershed scale as well as part of the site design process outlined above. Stormwater considerations may influence what type of development is appropriate for a site and/or the intensity of development allowed. Stormwater should be managed as close to the point of origin as possible. Collection and conveyance, especially structural systems, should be minimized. This is preferable from both an environmental and economic perspective. SWM infrastructure is expensive to build and even more costly to operate and maintain. Structural stormwater collection and conveyance systems also concentrate run-off and increase flows, leading to downstream degradation of instream habitat at the outfall. In the long-term, structural BMPs also tend to lose their effectiveness if not properly maintained and upgraded.

Stormwater management should also be comprehensive in scope, with BMPs designed to achieve multiple objectives. These objectives may include water quality treatment, water quantity control (peak, volume, and duration), flood protection considerations, channel protection criteria, and/or groundwater recharge considerations. In most cases a single BMP will not be effective in achieving all of these objectives. A multiple BMP or treatment-train approach will likely be required for most developments. In all cases the goal should be to solve the stormwater problem using the simplest approach possible. This relies on the use of low-impact site design, working with natural site features (non-structural BMPs), bio-treatment BMPs, and the judicious use of engineered SWM facilities. Prevention of water quality and run-off problems is critical to the success of the LID approach. In addition to minimizing stormwater, the low-impact approach emphasizes the use of natural areas and non-structural BMP's to treat stormwater on site. Structural BMPs may also be required, depending on site conditions, development intensity, and stormwater requirements.

Stormwater BMPs are distributed on each lot for residential development or evenly throughout the site, as much as possible, on commercial and industrial projects to mimic the natural processes of storage, detention, infiltration, and evapo-transpiration. They are also located to strategically filter pollutants. Some common techniques include:

- Rain gardens/bioretention
- Reduced size of stormwater pipes and detention culverts
- Depression storage in grassed and parking areas
- Infiltration devices
- Open drainage and infiltration swales
- Rooftop storage
- Green roofs
- Rainwater re-use (cisterns and rain barrels)
- Soil amendments (compost and organic matter)
- Soil rehabilitation (deep aeration and tilling)
- Reduced stormwater inlet size
- Planters

In order to protect the integrity of the downstream channels, it is important to maintain the timing of run-off (so-called time of concentration) from the site. LID designs accomplish this by using the following site design and grading techniques:

- Maintain natural drainage patterns
- Open drainage systems (swales and ditches)
- Flatten slopes
- Disperse drainage patterns
- Lengthen flow paths
- Save headwater areas from disturbance
- Increased setbacks from streams

The LID approach mainly addresses new development within the region, however full salmonid recovery cannot be achieved unless we also address existing development as well. All of the goals outlined above apply to existing development and many of the low-impact practices discussed here, are also applicable to existing development. However, BMP retrofitting tends to be much more difficult and costly than incorporation of this concepts into the original design. As with new development, reducing the impacts of existing development will require an integrated, watershed-specific, and prioritized approach to be successful in the long-term. It is also important to recognize that while streams in urbanized watersheds may be degraded and may have lost historic salmonid populations, they are no less important than those streams that still retain most of their natural ecological integrity. All aquatic systems play a role in the regional ecosystem and in the long-term recovery process. Key elements of a stormwater retrofit program for watersheds with existing development should include:

- Reduce impervious cover and replant native vegetation in key areas that drain directly to streams, lakes, and wetlands. The retention or reclamation of natural forest cover (especially mature coniferous forest) and wetland areas may be the single most influential factor to restoring the natural hydrologic regime of the urbanized watershed.
- Look for opportunities to rehabilitate or enhance the stream-riparian corridor. The purchase of property within the floodplain and riparian corridor should be a high priority. Riparian zones should be actively managed for a long-term goal of mature, coniferous-dominated forest throughout a majority of the riparian corridor. Until such time as natural levels of LWD recruitment are achieved, the installation of LWD may be required to achieve instream habitat goals.
- Identify stormwater "hotspots" (high pollutant source areas such as vehicle maintenance areas, high-volume parking lots, and industrial areas) and install water quality treatment devices (under-pavement BMP's such as sand or media filters and drain-inlet insert devices are strongly recommended).
- Consider the use of innovative ultra-urban BMPs for use in built-out areas where the retrofit of traditional stormwater BMPs is not feasible. Many of

these systems are designed to fit within existing catch basins, under paved areas, or stormwater manholes. The multi-chamber treatment train (MCTT) is one such device that has shown promise in other regions of the country.

- The use of high-efficiency street sweepers is strongly recommended for urban and high-density suburban areas or for industrial areas with high pollution potential.
- Evaluate all existing road crossing for possible removal or modification to reduce stormwater and instream impacts. This includes culvert assessment and replacement based on hydraulic criteria.
- Identify and eliminate all illicit stormwater discharges and combined sewer overflow (CSO) connections to the natural drainage system.
- Modify drainage conveyance systems to encourage bio-treatment (swales) and routing to stormwater BMPs. The goal should be to treat all run-off prior to discharging it to receiving waters.
- Retrofit existing structural BMPs to current SWM standards and look for opportunities to install new BMPs when space becomes available. Utilize infiltration or vegetative treatment (constructed wetlands or bio-retention) as a first choice where feasible.
- Implement an aggressive source-control program in all developed watersheds, with an emphasis on pollution prevention as well as salmon-friendly landscape and household management practices.
- Consider the use of parallel-pipe stormwater routing (a generally costly, last resort) to reduce the impacts of excessive run-off in highly urbanized watersheds where retention/detention opportunities are limited.
- Implement a road operation and maintenance program that minimizes the impact of road construction, operation, and maintenance activities. This road program should include a roadside ditch and shoulder upgrade component. All drainage ditches that drain to streams or wetlands should be converted into bio-treatment swales and maintained as such.
- Target agricultural NPS pollution sources (working farms, pasture areas, and hobby farms) for selective use of agricultural BMPs. This includes fencing of stream corridors, enhancement/rehabilitation of riparian buffers, and other appropriate techniques.
- Adopt "clean marina" and waterfront property owner programs. These programs utilize site design, source control, and stormwater BMP's to protect nearshore and estuary areas from the impacts of marina activities and shoreline development.

Reduction of pollutant loads and a well thought out maintenance plan are critical to the function of LID sites. The LID pollution prevention strategy includes initial notification of property owners about the requirements of maintaining LID sites and the mechanisms to ensure the long-term success and appearance of the development. Documents such as

educational pamphlets, covenants, and homeowners associations are key components. Some common practices for landowners include:

- Lawn care/hazardous waste management/recycling.
- Industry "good housekeeping" practices, proper disposal, spill prevention plans, and Manufacturers Safety Data Sheets (MSDS).
- Commercial businesses- alternative products and good housekeeping practices.

In summary, ecologically sound land use management of new development is the foundation of the integrated approach to SWM. Without some controls on land use any SWM strategy will only have limited effectiveness. The use of LID practices in other parts of the country have demonstrated their effectiveness in reducing cumulative impacts and protecting aquatic ecosystems (*Delaware DNR*, 1997). In addition, these developments have been shown to be more cost effective and have become quite popular with homebuyers. While these design principles and associated BMPs have not been tried in the PNW on this same scale, they hold much promise and should be evaluated for use in our region.

Low-impact site design and development principles emphasize conservation of natural areas, minimizing site disturbance, a significant reduction in impervious surfaces, and utilization of natural landscape features for stormwater treatment whenever possible. Recognizing that only natural areas retain full pre-development hydrologic characteristics, LID site design places a premium on maximizing these areas and minimizing the creation of excess run-off or water quality pollution. This approach tends to be more flexible than the current structural-only stormwater strategy in that it allows more flexibility in treatment options and more effective, site-specific BMP usage. In addition, LID tends to provide better run-off and pollutant reduction than conventional SWM practices. This is typically accomplished at a lower cost while using less watershed area. The goal of low-impact development is to maintain the pre-development hydrologic regime and protect the ecological integrity (physical, chemical, and biologic) of aquatic ecosystems within the watershed.

A summary of LID BMPs is included below. Drawings and site design guidance are included in Appendix O:

1. Impervious surface reduction – A variety of methods are available to reduce overall watershed imperviousness or %TIA, and especially those impervious surfaces that are directly connected to the natural drainage network (so-called effective imperviousness). The reduction of %EIA to near zero should be one of the primary watershed management goals. Narrow streets, shared driveways, and multi-level parking structures are examples of effective techniques for reducing imperviousness.
2. Natural vegetation retention – The conservation and restoration of natural forest and wetland cover should be a primary goal of a watershed management plan. Research throughout the country has demonstrated that natural vegetative cover is one of the most significant factors in maintaining natural

hydrologic function within the watershed (Figure 1). Natural areas also have other benefits, such as wildlife habitat, recreational areas, and for aesthetics.

3. Soil conservation and rehabilitation – The impact of urbanization on natural soil structure and function can be quite significant. During the development process, the most absorbent upper soil layers tend to be removed during grading and/or compacted by heavy equipment such that the natural permeability of the soil is destroyed or reduced significantly. Aeration and soil amendment using organic matter can restore some of the natural storage and infiltration capacity, but the conservation of natural soils is the most effective tool available.
4. Rainwater collection and re-use – Roof run-off can be collected in rain barrels or cisterns and used for landscape and lawn irrigation. Roof drains can also be routed to landscaped or turf areas via underground infiltration systems. In general, these infiltration systems should not be placed over septic drain fields. In addition, some jurisdictions allow for the reuse of rainwater for flushing toilets as part of an integrated "gray-water" reuse system within homes, offices, or businesses.
5. Rooftop gardens or green roofs – Large retail or office buildings have a significant rooftop impervious surface area component that could be reduced if the rooftop was vegetated. These eco-roofs are designed to capture rainfall from a specified storm event, treat it by biofiltration, and route the treated water to a water reuse system or to the stormwater network. A portion of the captured water will be returned to the atmosphere via evapo-transpiration and some will be retained within the rooftop vegetation. Green roofs also have energy savings benefits and can moderate building temperatures.
6. Pervious pavement – A wide variety of permeable pavers or porous surface treatments are available for use in walkways, patios, driveways, parking areas, and even roads with light traffic volumes. These techniques include concrete pavers, gravel-bed systems, and porous asphalt to name a few. Because, in typical urban watersheds, transportation-related impervious surfaces tend to make up a large percentage of overall imperviousness, any increase in permeability of these hard surfaces can be a significant positive benefit.
7. Disconnection of rooftops and paved areas – Disconnection of downspouts, driveways, sidewalks, parking lots, and roads from the stormwater conveyance network is another option for dealing with water quality and run-off quantity problems. Routing of run-off from these impervious surfaces into infiltration systems, dry wells, bioretention cells, or biofiltration swales/strips can reduce overall run-off volume and significantly improve downstream water quality.
8. Infiltration systems – The construction of structural BMPs such as infiltration trenches or basins can be an effective method of reducing run-off while treating the stormwater and restoring some groundwater recharge capacity. Care should be taken in using infiltration such that untreated stormwater is not allowed to come in contact with drinking water aquifers. In most case,

adequate pollutant removal is accomplished through a combination of biofiltration (running stormwater through vegetated swales or filter-strips) and percolation of stormwater through several layers of soil.

9. Biofiltration and bioretention – The use of vegetated BMPs to treat stormwater has been shown to be very effective for the removal of most common urban pollutants. Bioretention cells, bio-swales, vegetated roadside ditches, and biofiltration strips are all effective methods for water quality treatment and infiltration.

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ABBREVIATIONS

BFW .....Bankfull width
B-IBI .....Benthic index of biological integrity
BMP .....Best management practices
CAO .....Critical area ordinances
CMZ .....Channel migration zone
CSO .....Combined sewer overflow
CWA .....Clean Water Act
DD .....Drainage density
DO .....Dissolved oxygen
DoD .....Department of Defense
EA .....Environmental awareness
EIA .....Effective impervious area
ESA .....Endangered Species Act
GIS .....Geographical information system
HQI .....Habitat quality index
ITAM .....Integrated Training Area Management
LCTA .....Land Condition Trend Analysis
LID .....Low-impact development
LRAM .....Land Rehabilitation and Maintenance
LWD.....Large wood debris
MAMC .....Madigan Army Medical Center
MCTT.....Multi-chamber treatment train
MOU .....Memoranda of understanding
NPDES .....National Pollutant Discharge Elimination System
NPS .....Non-point source
PFC .....Properly functioning conditions
PNW.....Pacific Northwest
PQI .....Pool quality index
PSL.....Puget Sound lowland
PW.....Public works
RMZ .....Riparian management zone
RPD .....Residual pool depth
RQI.....Riffle quality index
SPSP.....South Puget Sound prairie
SWFPAC.....Strategic Weapons Facility Pacific
SWM .....Stormwater management
SWPPP .....Stormwater pollution prevention plan

TIA ..... Total impervious area
TRF ..... Trident refit facility
TRI ..... Training requirements integration
US EPA ..... U.S. Environmental Protection Agency
USFS ..... U.S. Forest Service
USGS ..... U.S. Geological Survey
UW-CUWRM... University of Washington, Center for Urban Water Resources Management
VFS ..... Vegetated filter strips
VLF ..... Very low frequency
WCC..... Washington Conservation Commission
WDFW ..... Washington Department of Fish and Wildlife
WDOE..... Washington Department of Ecology
WQ..... Water quality
WQI..... Wood quality index

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13. ABSTRACT *(Maximum 200 words)*

Several Department of Defense (DoD) installations in the Puget Sound region contain valuable aquatic habitat that supports threatened or endangered species of wildlife, including multiple species of salmonids and other aquatic biota. Little quantitative information about the habitat condition of most regional streams is available. This is true for streams within DoD jurisdiction as well. From June to November of 2000, the University of Washington conducted field surveys on military bases in the region. The goals of the habitat assessment project were threefold: (1) characterize the habitat quality, primarily for salmonids; (2) establish a baseline for future evaluation of trends in habitat quality and watershed function; and (3) inform the process of prioritizing areas for restoration and preservation.

14. SUBJECT TERMS
Salmonid habitat; watershed analysis; stream ecology; stormwater management

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Typical DoD Installation Activities and Associated Potential Environmental Impacts

Typical Installation Activities	Typical Impacts to Surface Water Quality														Typical Impacts to Ground Water Quality								Typical Impacts to Air Quality							Typical Impacts to Habitat					
	nutrients	explosives	BOD/COD	solids	pathogens	flooding	erosion	metals / inorganics	organics	Pesticides	hydrocarbons	supply/flow distruption	thermal pollution	uncontrolled spill/leak	nutrients	pathogens	metals / inorganic	organics	pesiticides	hydrocarbons	supply/flow distruption	uncontrolled spill/leak	noise	particulates	greenhouse gas	HAPs	SOx	NOx	uncontrolled release	decrease riparian buffer	decrease wetlands	increase invasive species	increase imperviousness	alter sensitive or endanered species habitat	decrease public support
Above ground storage tanks									x		x			x				x		x		x							x						
Agricultural leasing	x		x	x	x	x	x			x					x	x		x	x											x	x			x	
Aircraft maintenance activities		x		x			x	x	x		x		x	x			x	x		x			x			x			x	x	x			x	x
Ammunition supply points (ASP)				x			x		x		x							x		x			x	x	x					x				x	x
Amphibious landings and other training activities along or in water bodies	x		x		x				x		x				x	x		x		x															
Autocraft shops	x		x				x		x	x					x		x	x	x											x	x			x	
Bank or shoreline modification/stabilization				x		x	x																							x				x	
Battery management and storage		x					x	x	x								x	x					x			x			x	x	x			x	x
Boilers and heating plants (permited)			x	x				x	x		x		x	x			x	x		x		x	x	x	x	x	x	x	x						
Bulk fueling stations and transfer											x			x						x		x			x	x			x						x
Central compressed air plants																																			
Central hazardous material storage facilities (HAZMARTs)	x		x	x	x	x	x	x	x	x					x	x	x	x	x															x	x
Central steam plants and tunnels			x	x				x	x		x		x	x			x	x		x		x	x	x	x	x	x	x	x						
Chillers (permited)																																			
Coal pile storage	x		x					x	x		x		x				x	x		x			x	x	x	x	x	x	x						

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	nutrients	explosives	BOD/COD	solids	pathogens	flooding	erosion	metals / inorganics	organics	Pesticides	hydrocarbons	supply/flow distruption	thermal pollution	uncontrolled spill/leak	nutrients	pathogens	metals / inorganic	organics	pesiticides	hydrocarbons	supply/flow distruption	uncontrolled spill/leak	noise	particulates	greenhouse gas	HAPs	SOx	NOx	uncontrolled release	decrease riparian buffer	decrease wetlands	increase invasive species	increase imperviousness	alter sensitive or endanered species habitat	decrease public support
Concentrated animal feeding operations	x		x	x	x		x			x					x	x		x	x																
Concrete/asphalt plants																																			
Construction of large vehicle defensive positions		x																																	
Construction sites				x		x	x																								x			x	
Construction/demolition Landfills		x		x		x	x	x																										x	x
Contractor lay down area				x				x	x		x			x									x							x				x	
Controlled burns				x			x																	x	x					x				x	
Cooling towers and ponds	x		x	x				x	x		x		x	x			x	x		x		x	x	x	x	x	x	x	x						
Dams or other in stream flow regulations/modification devices								x	x				x																						
Defense reutilization and marketing offices (DRMOs)								x	x		x			x			x	x		x		x											x		
De-icing material application	x	x	x	x	x			x	x	x	x		x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x				x		x
Demolition				x			x		x		x							x		x			x	x	x					x				x	x
Demolition sites				x				x	x		x							x		x				x											
Dock and pier operations	x		x	x		x	x		x		x			x	x		x	x		x		x	x	x	x					x	x	x	x	x	
Domestic wastewater lagoon	x		x	x				x	x			x		x							x	x	x						x						

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Typical Installation Activities	Typical Impacts to Surface Water Quality														Typical Impacts to Ground Water Quality								Typical Impacts to Air Quality							Typical Impacts to Habitat					
	nutrients	explosives	BOD/COD	solids	pathogens	flooding	erosion	metals / inorganics	organics	Pesticides	hydrocarbons	supply/flow distruption	thermal pollution	uncontrolled spill/leak	nutrients	pathogens	metals / inorganic	organics	pesiticides	hydrocarbons	supply/flow distruption	uncontrolled spill/leak	noise	particulates	greenhouse gas	HAPs	SOx	NOx	uncontrolled release	decrease riparian buffer	decrease wetlands	increase invasive species	increase imperviousness	alter sensitive or endanered species habitat	decrease public support
Draining sites																																			
Dredging operations												x									x														
Drinking water treatment plant									x		x	x						x		x	x		x			x			x						
Drop zone clearing		x		x			x								x								x											x	
Dry cleaning operations									x				x					x								x									
Electrical substations						x	x					x	x																		x			x	
Emergency power (backup generators)	x	x	x	x		x	x		x		x			x	x		x	x		x		x	x	x	x									x	
Engine testing cells or pits									x				x																				x		
Engineer training areas (e.g., bridge building, shoreline stabilization, road and area clearing)				x		x	x		x					x				x																	
Equipment storage				x				x	x		x			x									x							x				x	
Excavation sites and borrow pits						x	x																								x			x	
Filling sites				x			x	x	x		x			x			x	x		x		x	x										x		
Fire breaks				x		x	x																									x		x	
Fire fighting training			x	x		x	x																							x				x	
Flight line ground support maintenance center								x									x																x		x

Typical DoD Installation Activities and Associated Potential Environmental Impacts

Typical Installation Activities	Typical Impacts to Surface Water Quality														Typical Impacts to Ground Water Quality								Typical Impacts to Air Quality							Typical Impacts to Habitat					
	nutrients	explosives	BOD/COD	solids	pathogens	flooding	erosion	metals / inorganics	organics	Pesticides	hydrocarbons	supply/flow distruption	thermal pollution	uncontrolled spill/leak	nutrients	pathogens	metals / inorganic	organics	pesiticides	hydrocarbons	supply/flow distruption	uncontrolled spill/leak	noise	particulates	greenhouse gas	HAPs	SOx	NOx	uncontrolled release	decrease riparian buffer	decrease wetlands	increase invasive species	increase imperviousness	alter sensitive or endanered species habitat	decrease public support
Foot-soldier training areas including obstacle courses and trails				x			x																x											x	
Golf cart/pesticide equipment wash facilities (100% recycle)				x																			x	x									x		
Golf courses	x		x	x	x		x								x	x																			
Grading sites				x		x	x																	x						x				x	
Ground water monitoring wells												x									x														
Ground water pump and treat facilities				x				x	x	x	x		x	x			x	x	x	x		x	x	x		x	x	x	x						
Ground water withdraw wells	x	x	x	x	x	x	x	x	x	x	x				x	x	x	x	x	x		x		x	x									x	x
Heavy vehicle washing operations				x				x	x		x			x			x	x		x		x	x	x	x	x			x						
Helicopter pad operations				x		x	x																								x			x	
Hobby shop	x		x	x	x		x								x	x																			
Horse stables	x		x	x	x		x				x			x									x		x							x		x	
Hospital, pharmacy, and other medical activities					x			x	x					x		x	x	x			x	x	x	x		x		x					x		
Housing areas	x		x	x	x	x	x			x	x	x		x	x	x			x	x	x	x			x								x		
HW incinerator		x		x				x	x	x	x			x			x	x	x	x		x				x			x						x
HW landfill		x		x				x	x	x	x			x			x	x	x	x		x				x			x						x

Typical DoD Installation Activities and Associated Potential Environmental Impacts

Typical Installation Activities	Typical Impacts to Surface Water Quality														Typical Impacts to Ground Water Quality								Typical Impacts to Air Quality							Typical Impacts to Habitat					
	nutrients	explosives	BOD/COD	solids	pathogens	flooding	erosion	metals / inorganics	organics	Pesticides	hydrocarbons	supply/flow distruption	thermal pollution	uncontrolled spill/leak	nutrients	pathogens	metals / inorganic	organics	pesiticides	hydrocarbons	supply/flow distruption	uncontrolled spill/leak	noise	particulates	greenhouse gas	HAPs	SOx	NOx	uncontrolled release	decrease riparian buffer	decrease wetlands	increase invasive species	increase imperviousness	alter sensitive or endanered species habitat	decrease public support
HW storage facilities																																			
HW treatment facilities	x	x	x	x				x	x	x	x			x			x	x	x	x		x	x			x			x						
Illicit discharges (not previously noted)	x		x	x	x		x	x	x	x	x				x	x	x	x	x	x	x													x	
Industrial laundries								x	x					x			x	x				x													
Industrial printing								x	x								x	x					x			x	x	x							
Industrial wastewater treatment plant	x		x	x	x		x	x							x	x	x																	x	
Installation restoration activities				x			x	x	x		x						x	x		x	x	x	x	x		x			x					x	x
Invasive vegative management										x									x																
Laboratories (Research)	x		x						x						x			x																	
Laboratories and research areas		x		x	x			x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x				x		x
Land application of sanitary wastewater						x						x																						x	
Land disposal of sludge				x	x			x	x				x	x		x	x	x		x		x	x	x		x		x	x						
Large arms impact areas (active)		x						x	x		x			x						x		x	x	x	x										
Large arms impact areas (inactive)				x	x	x	x		x	x	x				x	x	x	x	x	x			x	x	x					x			x	x	
Light vehicle washing operations				x				x			x			x			x			x		x	x					x							x

Typical DoD Installation Activities and Associated Potential Environmental Impacts

Typical Installation Activities	Typical Impacts to Surface Water Quality														Typical Impacts to Ground Water Quality								Typical Impacts to Air Quality							Typical Impacts to Habitat					
	nutrients	explosives	BOD/COD	solids	pathogens	flooding	erosion	metals / inorganics	organics	Pesticides	hydrocarbons	supply/flow distruption	thermal pollution	uncontrolled spill/leak	nutrients	pathogens	metals / inorganic	organics	pesiticides	hydrocarbons	supply/flow distruption	uncontrolled spill/leak	noise	particulates	greenhouse gas	HAPs	SOx	NOx	uncontrolled release	decrease riparian buffer	decrease wetlands	increase invasive species	increase imperviousness	alter sensitive or endanered species habitat	decrease public support
Livestock grazing	x		x	x			x			x					x				x														x		
Logging road construction/maintenance				x		x	x																									x		x	
Low water crossings (tactical vehicle use)		x		x			x	x	x								x	x					x			x			x	x	x			x	x
Maintenance of training roads		x						x	x								x	x					x			x			x	x	x			x	x
Major landscaping activities				x		x	x																										x		
Manmade ponds, reservoirs or lagoons				x				x	x		x			x			x	x		x		x													
Marinas and recreational boating								x	x		x			x			x	x		x		x											x		
Medical Waste Incinerators	x		x	x	x	x	x	x	x	x	x				x	x	x	x	x	x		x		x	x									x	x
Missle/bomb disassembly																																			
Motor pools and vehicle maintenance centers																																			
Mowing and clearing																							x										x	x	
Munition/propellent manufacturing	x	x		x				x	x		x		x				x	x		x			x	x		x			x	x		x	x		x
National priority list site				x			x	x	x		x						x	x		x	x	x	x	x		x			x					x	x
Non-contact cooling water discharges.	x		x	x	x	x	x	x	x	x	x				x	x	x	x	x	x		x		x	x									x	x
Nondischarging wastewater treatment/disposal lagoons (evaporation ponds)				x		x	x																							x	x	x	x	x	

Typical DoD Installation Activities and Associated Potential Environmental Impacts

Typical Installation Activities	Typical Impacts to Surface Water Quality														Typical Impacts to Ground Water Quality								Typical Impacts to Air Quality							Typical Impacts to Habitat					
	nutrients	explosives	BOD/COD	solids	pathogens	flooding	erosion	metals / inorganics	organics	Pesticides	hydrocarbons	supply/flow distruption	thermal pollution	uncontrolled spill/leak	nutrients	pathogens	metals / inorganic	organics	pesiticides	hydrocarbons	supply/flow distruption	uncontrolled spill/leak	noise	particulates	greenhouse gas	HAPs	SOx	NOx	uncontrolled release	decrease riparian buffer	decrease wetlands	increase invasive species	increase imperviousness	alter sensitive or endanered species habitat	decrease public support
Off road vehicle usage				x		x	x																										x	x	
Oil and wood handling sites at power generation plants	x		x	x		x	x				x				x				x				x		x			x					x	x	
Oil transfer stations (pump stations/pipe lines)	x		x	x				x	x		x			x			x	x	x	x		x	x		x	x		x					x		
Open anchorage	x		x		x						x			x											x		x	x	x			x			
Open burning				x				x			x						x			x															
Open detonation				x				x			x						x			x															
Ore piles, (National reserve stockpiles)	x		x	x	x			x	x	x	x	x	x	x	x	x	x	x				x	x					x	x						
Other recreational activities (jogging trails, baseball fields, tennis courts, etc.)			x	x				x	x	x	x		x	x			x	x	x	x		x	x										x		
Outdoor recreation centers (rentals), RV parks, campgrounds			x	x				x	x		x		x	x			x	x		x		x	x										x		
Paint and spray paint booths				x				x	x		x			x			x	x		x		x	x		x	x							x		
Parking lots						x	x	x			x			x			x			x		x								x	x		x	x	
Personnel exchange, commisary, and other shops				x	x	x	x				x		x	x						x		x											x		
Personnel vehicle maintenance and washing area					x			x			x		x	x	x	x		x		x		x			x							x		x	
Photographic processing								x	x								x	x																	
Pipe construction and installation				x		x	x																x											x	

Typical DoD Installation Activities and Associated Potential Environmental Impacts

Typical Installation Activities	Typical Impacts to Surface Water Quality														Typical Impacts to Ground Water Quality								Typical Impacts to Air Quality							Typical Impacts to Habitat					
	nutrients	explosives	BOD/COD	solids	pathogens	flooding	erosion	metals / inorganics	organics	Pesticides	hydrocarbons	supply/flow distruption	thermal pollution	uncontrolled spill/leak	nutrients	pathogens	metals / inorganic	organics	pesiticides	hydrocarbons	supply/flow distruption	uncontrolled spill/leak	noise	particulates	greenhouse gas	HAPs	SOx	NOx	uncontrolled release	decrease riparian buffer	decrease wetlands	increase invasive species	increase imperviousness	alter sensitive or endanered species habitat	decrease public support
Pit/chemical latrines				x			x				x									x			x	x	x									x	
Power generation using coal	x		x					x	x		x		x				x	x		x			x	x	x	x	x	x	x						
Power generation using fuel oil	x		x	x				x	x		x		x	x			x	x		x		x	x	x	x	x	x	x	x						
Rail tank car loading/unloading racks (EPCRA chemicals, white phosphorus, etc)	x		x		x										x	x					x														
Railroad access and loading				x		x	x				x									x			x	x	x	x	x	x	x			x		x	
Recycling collection and processing	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						x
Remodeling/retrofitting structures				x			x		x		x			x				x		x		x	x												
Road maintenance - paved				x		x	x																									x	x	x	
Runway/flight line operations		x					x	x	x		x						x	x		x			x	x		x			x					x	x
Salt/sand storage				x				x									x																	x	
Sanitary landfills - active				x	x					x																						x	x		
Sanitary landfills -closed															x	x	x	x	x	x	x														x
Sanitary wastewater treatment plant	x	x	x		x				x					x	x	x						x													
Septic systems/onsite treatment systems	x		x	x		x	x																											x	
Ship building, maintenance and repair		x		x			x	x	x		x						x	x		x			x	x		x			x					x	x

Typical DoD Installation Activities and Associated Potential Environmental Impacts

Typical Installation Activities	Typical Impacts to Surface Water Quality														Typical Impacts to Ground Water Quality								Typical Impacts to Air Quality							Typical Impacts to Habitat					
	nutrients	explosives	BOD/COD	solids	pathogens	flooding	erosion	metals / inorganics	organics	Pesticides	hydrocarbons	supply/flow distruption	thermal pollution	uncontrolled spill/leak	nutrients	pathogens	metals / inorganic	organics	pesiticides	hydrocarbons	supply/flow distruption	uncontrolled spill/leak	noise	particulates	greenhouse gas	HAPs	SOx	NOx	uncontrolled release	decrease riparian buffer	decrease wetlands	increase invasive species	increase imperviousness	alter sensitive or endanered species habitat	decrease public support
Small arms ranges				x			x	x									x						x												x
Solid waste management unit not covered in a previous installation activity		x																																	
Stocking of ponds and lakes for fishing														x																			x		
Storage and application of fertilizers	x		x											x	x							x													
Storage and application of pesticides and herbicides									x	x				x					x			x													
Storage and warehouse areas		x		x				x	x	x	x			x			x	x	x	x		x				x			x						x
Storage sites for Mobile POL Tankers																																			
Stormwater retention and conveyences (maintenance, retrofitting and construction)	x		x	x	x	x	x	x	x	x	x				x	x	x	x	x	x		x		x	x						x			x	x
Swimming pools																																x		x	
Test ranges and facilities								x	x					x				x		x		x		x		x			x						
Test tracks (such as Churchville at APG)				x		x	x	x	x	x	x		x	x			x	x	x	x		x	x	x	x	x	x	x	x				x	x	x
Timber harvesting and forest management				x		x	x						x										x							x				x	
Troop encampments				x	x	x	x		x	x	x				x	x	x	x	x	x			x	x	x					x			x	x	
Underground injection wells				x				x	x	x	x			x			x	x	x	x		x										x	x		
Underground storage tanks																		x		x		x							x						

Typical DoD Installation Activities and Associated Potential Environmental Impacts

Typical Installation Activities	Typical Impacts to Surface Water Quality														Typical Impacts to Ground Water Quality								Typical Impacts to Air Quality							Typical Impacts to Habitat					
	nutrients	explosives	BOD/COD	solids	pathogens	flooding	erosion	metals / inorganics	organics	Pesticides	hydrocarbons	supply/flow distruption	thermal pollution	uncontrolled spill/leak	nutrients	pathogens	metals / inorganic	organics	pesiticides	hydrocarbons	supply/flow distruption	uncontrolled spill/leak	noise	particulates	greenhouse gas	HAPs	SOx	NOx	uncontrolled release	decrease riparian buffer	decrease wetlands	increase invasive species	increase imperviousness	alter sensitive or endanered species habitat	decrease public support
Vehicle fueling stations								x	x		x			x			x	x		x		x	x	x	x				x				x		
Vehicle storage areas				x				x	x		x			x			x	x		x		x	x	x	x	x	x	x	x					x	
Wastewater collection systems	x	x	x		x				x					x	x	x						x													
Wildlife management (managed hunts, traping, poison)										x									x															x	
X-ray inspection (film development)											x			x						x		x											x		

Typical DoD Installation Activities and Regulations Governing Associated Potential Environmental Impacts

Typical Installation Activities	Typical Source to Find Information about Installation Activity	Typical Compliance Burden	
		Law/Reg Typically Regulating Activity Operations	Applicable Types of Permits/Plans
Above ground storage tanks	ICCP/SPCCP, SWPPP	RCRA-C, CWA, CAA, EPCRA	NPDES-SW, ICCP/SPCCP, Source Water Protection Plan
Agricultural leasing	INRMP, SWPPP	CWA	NPDES-SW
Aircraft maintenance activities	SWPPP	CWA	
Ammunition supply points (ASP)		CWA	
Amphibious landings and other training activities along or in water bodies	INRMP, SWPPP	ESA	
Autocraft shops		CWA	NPDES-SW
Bank or shoreline modification/stabilization	INRMP, SWPPP, Master Plan	CWA	NPDES-SW
Battery management and storage	SWPPP	CWA, SDWA	
Boilers and heating plants (permited)	SWPPP	CWA	
Bulk fueling stations and transfer	ICCP/SPCCP, SWPPP	RCRA-C, CWA, CAA, EPCRA	NPDES-SW, ICCP/SPCCP, Source Water Protection Plan
Central compressed air plants			
Central Hazardous Material storage facilities (HAZMARTs)		CWA, CAA	NPDES-SW
Central steam plants and tunnels		CWA	
Chillers (permited)	SWPPP, NPDES	CWA	
Coal pile storage	SWPPP	CWA, SDWA	
Concentrated animal feeding operations	INRMP, SWPPP	CWA	NPDES-SW
Concrete/asphalt plants		CWA, SDWA	
Construction of large vehicle defensive positions	INRMP, SWPPP	CWA	NPDES -SW
Construction sites	SWPPP	CWA	NPDES-SW
Construction/demolition landfills		CWA, ESA	CWA 404 Permit
Contractor lay down area	SWPPP	CWA	
Controlled burns	INRMP, SWPPP	CWA, CAA	NPDES-SW, CAA
Cooling towers and ponds		RCRA-C, CWA, CAA, EPCRA	NPDES, CAA, Source Water Protection Plan
Dams or other in stream flow regulations/modification devices	INRMP, SWPPP	CWA	NPDES

Typical DoD Installation Activities and Regulations Governing Associated Potential Environmental Impacts

Typical Installation Activities	Typical Source to Find Information about Installation Activity	Typical Compliance Burden	
		Law/Reg Typically Regulating Activity Operations	Applicable Types of Permits/Plans
Defense reutilization and marketing offices (DRMOs)	RCRA-D, SWPPP	RCRA-D, CWA, CAA	RCRA-D, NPDES-SW, CAA
De-icing material application	SWPPP	CWA	
Demolition	SWPPP	CWA, ESA	NPDES-SW
Demolition sites	INRMP, SWPPP, Master Plan	RCRA-D, CWA, CAA	NPDES-SW, ICCP/SPCCP, Source Water Protection Plan
Dock and pier operations	INRMP, SWPPP, Master Plan	RCRA-D, CWA	NPDES-SW
Domestic wastewater lagoon	NPDES Permit, SWPPP	SDWA, CWA, RCRA-C	SDWA, Source Water Protection Plan
Draining sites	INRMP, SWPPP, Master Plan	RCRA-D, CWA, CAA	NPDES-SW, ICCP/SPCCP, Source Water Protection Plan
Dredging operations	INRMP, CWA Permit, SWPPP	SDWA, CWA, RCRA-C	Source water protection plan
Drinking water treatment plant	Source Water Protection Plan, SDWA Permit, Master Plan, SWPPP	SDWA, CWA, RCRA-C	RCRA-C, NPDES-SW, CAA
Drop zone clearing	INRMP, SWPPP	CWA, ESA	NPDES-SW
Dry cleaning operations	NPDES Pretreatment Program, Air Emissions Inventory	CWA, CAA	NPDES-PRE, CAA
Electrical substations		CWA, ESA	COE Permit
Emergency power (backup generators)		RCRA-D, CWA, CAA	NPDES-SW
Engine testing cells or pits	SWPPP	CWA, CAA	
Engineer training areas (e.g., bridge building, shoreline stabilization, road and area clearing)	SWPPP, Master Plan	RCRA-D, CWA	NPDES-SW
Equipment storage	INRMP, SWPPP, Master Plan	CWA, CAA	
Excavation sites and borrow pits	INRMP, SWPPP, Master Plan	CWA	NPDES-SW
Filling sites	INRMP, SWPPP, Master Plan	RCRA-C, CWA	NPDES-SW
Fire breaks	INRMP, SWPPP	CWA	NPDES-SW
Fire fighting training	INRMP, SWPPP	CWA,ESA	NPDES-SW
Flight line ground support maintenance center		CWA	NPDES-SW
Foot-soldier training areas including obstacle courses and trails	SWPPP, Master Plan	CWA	NPDES-SW
Golf cart/pesticide equipment wash facilities (100% recycle)		CWA, CAA	NPDES -SW
Golf courses	SWPPP, Pest Management Plan	CWA	NPDES-SW

Typical DoD Installation Activities and Regulations Governing Associated Potential Environmental Impacts

Typical Installation Activities	Typical Source to Find Information about Installation Activity	Typical Compliance Burden	
		Law/Reg Typically Regulating Activity Operations	Applicable Types of Permits/Plans
Grading sites	INRMP, SWPPP, Master Plan	CWA	NPDES-SW
Ground water monitoring wells	Source Water Protection Plan, SDWA Permit, Master Plan	SDWA, CWA, RCRA-C	SWPP
Ground water pump and treat facilities	RCRA-C Permit, SWPPP, Source Water Protection Plan,	RCRA-C, CWA, SDWA	RCRA-C, NPDES, CAA
Ground water withdraw wells	Source Water Protection Plan, SDWA Permit, Master Plan	RCRA-C, CWA, SDWA	RCRA-C, NPDES, CAA
Heavy vehicle washing operations	SWPPP	CWA	NPDES-SW
Helicopter pad operations	INRMP, SWPPP, Master Plan	CWA	NPDES-SW
Hobby shop	SWPPP	CWA	NPDES-SW
Horse stables	SWPPP	CWA	
Hospital, pharmacy, and other medical activities	NPDES Pretreatment Program, Air Emissions Inventory	RCRA, CWA, CAA	NPDES-PRE, RCRA C, CAA
Housing areas	SWPPP	CWA	NPDES -SW
HW incinerator	RCRA-C Permit, SWPPP	RCRA-C, CWA, CAA	RCRA-C, NPDES, CAA
HW landfill	RCRA-C Permit, SWPPP	RCRA-C, CWA, CAA	RCRA-C, NPDES, CAA
HW storage facilities	RCRA-C Permit, SWPPP	CWA	NPDES
HW treatment facilities	RCRA-C Permit, SWPPP	RCRA-C, CWA, CAA	NPDES, CAA
Illicit discharges (not previously noted)	SWPPP	CWA	NPDES
Industrial laundries	SWPPP	RCRA-C, CWA, CAA	RCRA-C, NPDES-SW, CAA
Industrial printing	SWPPP	RCRA, CWA, CAA	
Industrial wastewater treatment plant	NPDES Permit, SWPPP, Master Plan	RCRA-D, CWA	RCRA-D, State land application permit
Installation restoration activities	IRP, SWPPP	RCRA, CERCLA, CWA, CAA	NPDES, RCRA
Invasive vegative management	INRMP, SWPPP	ESA	
Laboratories (Research)	SWPPP	RCRA-C, CWA	NPDES-SW
Laboratories and research areas	NPDES Pretreatment Program, Air Emissions Inventory	CWA, CAA	NPDES-PRE, RCRA C, CAA
Land application of sanitary wastewater	SWPPP, State Land Application Permit	CWA, ESA	
Land disposal of sludge	SWPPP, State Land Application Permit	RCRA-I, CWA, CAA	RCRA, CAA

Typical DoD Installation Activities and Regulations Governing Associated Potential Environmental Impacts

Typical Installation Activities	Typical Source to Find Information about Installation Activity	Typical Compliance Burden	
		Law/Reg Typically Regulating Activity Operations	Applicable Types of Permits/Plans
Large arms impact areas (active)	INRMP, SWPPP, Master Plan	RCRA-C, CWA, CAA	NPDES-SW, CAA
Large arms impact areas (inactive)	INRMP, SWPPP, Master Plan	CWA	NPDES-SW
Light vehicle washing operations	SWPPP	RCRA-C, CWA, CAA	RCRA-C, NPDES-SW, CAA
Livestock grazing	SWPPP	CWA	NPDES -SW
Logging road construction/maintenance	INRMP, SWPPP	CWA	NPDES-SW
Low water crossings (tactical vehicle use)		RCRA-C, CWA, CAA, ESA	NPDES-SW, INRMP, Soil Erosion Control Plan
Maintenance of training roads	INRMP, SWPPP, Master Plan	RCRA-C, CWA, CAA, ESA	NPDES-SW, INRMP, Soil Erosion Control Plan
Major landscaping activities	INRMP, SWPPP, Master Plan	CWA	NPDES-SW
Manmade ponds, reservoirs or lagoons	SWPPP, Master Plan	RCRA-C, RCRA-D, CWA, CAA	RCRA, NPDES, CAA
Marinas and recreational boating	INRMP	CWA, CAA	NPDES -SW
Medical Waste Incinerators	RCRA-I Permit, SWPPP	RCRA D, CWA, CAA	RCRA-D, NPDES-SW, CAA
Missle/bomb disassembly		CWA	
Motor pools and vehicle maintenance centers	SWPPP	CWA	NPDES-SW
Mowing and clearing	INRMP, SWPPP, Master Plan, Grounds Maintenance Contract	CWA	NPDES-SW
Munition/propellent manufacturing		CWA	NPDES-SW
National priority list site	IRP, SWPPP	RCRA, CERCLA, CWA, CAA	NPDES, RCRA
Non-contact cooling water discharges.		RCRA D, CWA, CAA	RCRA-D, NPDES-SW, CAA
Nondischarging wastewater treatment/disposal lagoons (evaporation ponds)		CWA	NPDES-SW
off road vehicle usage	INRMP, SWPPP, Master Plan	CWA,ESA	NPDES-SW, INRMP, Soil Erosion Control Plan
Oil and wood handling sites at power generation plants	SWPPP, Master Plan	CWA	NPDES-SW
Oil transfer stations (pump stations/pipe lines)		RCRA-C, CWA, EPCRA	NPDES-SW
Open anchorage	SWPPP, Master Plan	CWA	NPDES-SW
Open burning	RCRA Subpart X Permit, SWPPP	RCRA-C, CWA, CAA	NPDES-SW
Open detonation	RCRA Subpart X Permit, SWPPP	RCRA-C, CWA, CAA	NPDES-SW

Typical DoD Installation Activities and Regulations Governing Associated Potential Environmental Impacts

Typical Installation Activities	Typical Source to Find Information about Installation Activity	Typical Compliance Burden	
		Law/Reg Typically Regulating Activity Operations	Applicable Types of Permits/Plans
Ore piles, (National reserve stockpiles)		CWA, CAA, RCRA-D, RCRA-C	NPDES, RCRA-C, CAA
Other recreational activities (jogging trails, baseball fields, tennis courts, etc.)	SWPPP, Pest Management Plan	ESA	
Outdoor recreation centers (rentals), RV parks, campgrounds		ESA	
Paint and spray paint booths	SWPPP, Air emissions inventory	RCRA-C, CWA, CAA	RCRA-C, NPDES-SW, CAA
Parking lots	SWPPP, Master Plan	CWA	NPDES-SW
Personnel exchange, commisary, and other shops	SWPPP	RCRA, CWA, CAA	NPDES -SW
Personnel vehicle maintenance and washing area	SWPPP	CWA	NPDES -SW
Photographic processing	NPDES Pretreatment Program	CWA, CAA	NPDES-PRE, CAA
Pipe construction and installation	SWPPP, Master Plan	CWA	NPDES-SW
Pit/chemical latrines		CWA,ESA	NPDES-SW, INRMP, Soil Erosion Control Plan
Power generation using coal	SWPPP, Master Plan	CWA, CAA	NPDES-SW
Power generation using fuel oil	SWPPP, Master Plan	CWA, CAA	NPDES-SW
Rail tank car loading/unloading racks (EPCRA chemicals, white phosphorus, etc)		CWA, SDWA	n/a
Railroad access and loading	SWPPP, Master Plan	CWA	NPDES-SW
Recycling collection and processing	RCRA-D Permit, SWPPP	RCRA, CWA, CAA	RCRA D, NPDES-SW
Remodeling/retrofitting structures	SWPPP, Master Plan	CWA	NPDES-SW
Road maintenance - paved	SWPPP, Master Plan	CWA	NPDES-SW
Runway/flight line operations	SWPPP	RCRA-X, CWA, CAA	RCRA-X, NPDES-SW, CAA
Salt/sand storage	SWPPP, Master Plan	CWA	NPDES-SW
Sanitary landfills - active	RCRA-D Permit, SWPPP	CWA	NPDES
Sanitary landfills -closed	RCRA-D Permit, SWPPP	SDWA, CWA, RCRA-C	RCRA, UIC Permit, Source water protection plan
Sanitary wastewater treatment plant	NPDES Permit, SWPPP	CWA	NPDES
Septic systems/onsite treatment systems	Master Plan, SWPPP	CWA, ESA	NPDES-SW
Ship building, maintenance and repair	SWPPP	RCRA-X, CWA, CAA	RCRA-X, NPDES-SW, CAA

Typical DoD Installation Activities and Regulations Governing Associated Potential Environmental Impacts

Typical Installation Activities	Typical Source to Find Information about Installation Activity	Typical Compliance Burden	
		Law/Reg Typically Regulating Activity Operations	Applicable Types of Permits/Plans
Small arms ranges	INRMP, SWPPP, Master Plan	RCRA-C, CWA, CAA	NPDES-SW, INRMP, Soil Erosion Control Plan
Solid waste management unit not covered in a previous installation activity	RCRA D Permit, SWPPP	RCRA-C, CWA, CAA	
Stocking of ponds and lakes for fishing	INRMP	ESA	
Storage and application of fertilizers	SWPPP, Pest Management Plan	RCRA-C, CWA, SDWA	NPDES-SW, ICCP/SPCCP, Source Water Protection Plan
Storage and application of pesticides and herbicides	SWPPP, Pest Management Plan	RCRA-C, CWA, SDWA	NPDES-SW, ICCP/SPCCP, Source Water Protection Plan
Storage and warehouse areas	RCRA-C Permit, SWPPP, SPCCP/ICCP	RCRA-C, CWA, CAA	NPDES-SW, ICCP/SPCCP, Source Water Protection Plan
Storage sites for Mobile POL Tankers			
Stormwater retention and conveyences (maintenance, retrofitting and construction)	Master Plan, SWPPP		
Swimming pools		CWA, Sikes Act	INRMP
Test ranges and facilities		RCRA-C, CWA, CAA	NPDES-SW, CAA
Test tracks (such as Churchville at APG)		RCRA-C, CWA, CAA	NPDES-SW
Timber harvesting and forest management	INRMP, SWPPP	CWA	NPDES-SW
Troop encampments	INRMP, SWPPP, Master Plan	CWA, ESA	NPDES-SW, INRMP, Soil Erosion Control Plan
Underground injection wells	RCRA I, Source Water Protection Plan, SWPPP		
Underground storage tanks	ICCP/SPCCP, SWPPP	RCRA-C, CWA, CAA, EPCRA	NPDES-SW, ICCP/SPCCP, Source Water Protection Plan
Vehicle fueling stations	ICCP/SPCCP, SWPPP	RCRA-C, CWA, CAA, EPCRA	NPDES-SW, ICCP/SPCCP, Source Water Protection Plan
Vehicle storage areas	SWPPP	RCRA-C, CWA, CAA	NPDES-SW
Wastewater collection systems	NPDES Permit, SWPPP		
Wildlife management (managed hunts, traping, poison)	INRMP, SWPPP	CWA, ESA	N/A
X-ray inspection (film development)		RCRA-C, CWA, CAA	NPDES-SW

Although the Clean Water Act (CWA) is the primary law driving watershed management policies, DoD environmental managers should be aware of a variety of other environmental laws, executive orders, and voluntary agreements that influence and can be affected by watershed management issues. Appendix A-3 lists relevant laws, executive orders, and DoD Instructions. A description of each is provided along with the relationship to watershed management.

Category	Title	Relationship to Watershed Management
Federal laws	Clean Water Act	• Basis for watershed management, including NPDES, nonpoint source pollution control, TMDLs, and watershed management. All watershed management activities must be consistent with the Clean Water Act and state watershed management activities.
	Estuaries and Clean Waters Act of 2000	• All Chesapeake Bay agreements are codified. DoD installations must comply with the Chesapeake Bay agreements and plans in a manner that is consistent with your mission and success in securing the necessary resources. • DoD shall participate in regional and sub-watershed planning and restoration programs. • If the Chesapeake Bay watershed is not off the impaired waterbodies list, it will be subject to TMDL requirements, which may mean stricter discharge limits to DoD installations in the watershed. • Promotes restoring estuary habitat. Potential partnering with local estuary habitat restoration projects.
	Safe Drinking Water Act	• Requires source water protection and wellhead protection plans that can be integrated into other watershed protection efforts like point and nonpoint source pollution control, wetlands protection, waste management, air pollution, and pesticide management. Watershed management efforts must not conflict with source water protection and wellhead protection plans. This integration of efforts will allow various watershed stakeholders to look for opportunities to leverage limited resources to meet common goals.
	Coastal Zone Management Act of 1972	• State may have stricter water quality and land use activity requirements in the coastal zone area due to specific coastal zone nonpoint source pollution requirements, which build upon the state's watershed protection efforts. DoD activities within the coastal zone, and those activities outside but can affect resources inside the coastal zone can be subject to the requirements.
	Sikes Act	Watershed protection enhances the natural ecosystem. Thus, it promotes the planning, development and maintenance of fish and wildlife resources on military reservations. The Integrated Natural Resource Management Plans should be incorporate the watershed management assessment ideas and concepts and vice versa.

Category	Title	Relationship to Watershed Management
	Clean Air Act	• Pollutants of concern can affect water quality through air deposition. Air pollution contributors may be required to reduce sources of pollutants through air permits, pollution control and reduction, and multi media programs to meet TMDL standards.
	Comprehensive Environmental Restoration, Cleanup and Liability Act (CERCLA)	• For those NPL sites that effect surface and ground water quality that do not have approved cleanup plans may require more stringent clean-up and monitoring to meet requirements TMDL standards.
	Emergency Planning and Community Right-to-Know Act (EPCRA)	• Installations can expand upon their community relationships from EPCRA to identify watershed improvement partnering opportunities and educate other watershed stakeholders on the installation's efforts and the importance of watershed protection. Also, the installation contingency plans and TRI reports identify activities that may have an impact on the watershed.
	Endangered Species Act (ESA)	• Watershed activities must be consistent with recovery plans.
	Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)	• By complying with FIFRA, installations decrease the potential of water pollution associated with pest management..
	National Environmental Policy Act (NEPA)	• Watershed approach expands upon NEPA's interdisciplinary approach by assessing all activities that may influence water quality and ecosystem health. • Some watershed management recommendations may require a NEPA environmental assessment.
	Toxic Substances Control Act	• Elimination or reduce use of substances that are found to be toxic will reduce the chances of the substance entering the watershed and associated ecosystem.

Category	Title	Relationship to Watershed Management
	Resource Conservation and Recovery Act (RCRA)	• RCRA operating permits that have discharge limits may be revised in watersheds that are undergoing the TMDL process. For example, RCRA requires that landfills be operated in a manner that does not degrade surface water or ground water quality. Therefore, if a TMDL is developed for the watershed that targets pollutants released by the landfill, the permit may be revised to to meet TMDL standards. • Closed landfills are a semi-pervious land use that support vegetation and various habitats, while allowing adsorption and intake of surface water through the soil and vegetation; thus, reducing sediment and other pollutant loads to surface water. • Proper handling, shipping, treatment, and disposal of hazardous and solid wastes reduces the chances of the wastes entering surface or ground water and effecting ecosystems.
Executive orders	13148, Greening the Government Through Leadership in Environmental Management	• The EO requires that federal facilities adopt beneficial landscaping practices. Implementing the EO may decrease pollutants that can affect watershed and water quality.
	13112, Invasive Species	• Replacing invasive plants with native plants can improve soil stabilization and nutrient uptake. • Removing invasive animals can improve health of plants and decrease their negative effects on ecosystem balance, thus improving watershed and water quality.
	13093, American Heritage Rivers	• Activities that influence an American Heritage river should be coordinated with the American Heritage "River Navigator" to ensure they support the community's implementation plans. • Work with River Navigator to encourage community involvement in sustaining the river and surrounding watershed.
	12902, Energy Efficiency and Water Conservation at Federal Facilities	• Conserving water decreases the amount that needs treatment and the amount removed from the watershed. Currently, the Clean Water Act does not regulate quantity; however, it may be regulated in the future. If it does, installations may be required to curtail water consumption as part of a TDML requirement.
	12088, Federal Compliance with Pollution Control Standards	• Pollution prevention of toxic or solid wastes reduces the chances of the wastes entering surface or ground water and effecting ecosystems and drinking water.

Category	Title	Relationship to Watershed Management
	12898, Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations	• Watershed management activities should include environmental justice principles and support environmental justice to minority populations and low-income populations.
	12856, Federal Compliance with Right-to-Know Laws and Pollution Prevention Requirements	When selecting watershed activities, consider those that are source reduction pollution prevention measures and encourage markets for clean technologies and safe alternatives to extremely hazardous substances or toxic chemicals.
	11988, Floodplain Management	• Limiting activities on the floodplain will minimize environmental impact, and restore/preserve the natural land values.
	11288, Prevention, Control, and Abatement of Water Pollution by Federal Activities	• Installations must follow water quality discharging laws as well as permitting. Current water pollution shall be controlled and new buildings will be required to meet minimal water pollution prevention, control and abatement standards. This approach is consistent with watershed management.
	11593, Protection and Enhancement of the Cultural Environment	• Watershed management should be consistent with cultural resource preservation, restoration, and maintenance activities. All cultural resource activities should be conducted in a manner as to not degrade the watershed health, such as silt fences.
	11990, Protection of Wetlands	• Watershed protection is consistent with wetlands protection. Any watershed management approach should not degrade or reduce wetlands.
DoDIs	DoDD 4001.1, Installation Management	• Watershed management can complement installation management by decreasing costs and maintenance while improving the aesthetics of the installation.
	DoDD 4165.61, Intergovernmental Coordination of DoD Federal Development Programs and Activities	• Watershed management activities should be coordinated with all watershed stakeholders.
	DoDI 4165.57, Air Installation Compatible Use Zones	• Watershed management activities should be consistent with the AICUZ plans and can build upon the community relationships to implement watershed management activities with watershed stakeholders.
	DoDD 5000.1, Defense Acquisition	• Defense acquisitions should be made in a manner that will not result in impairments the watershed.

Category	Title	Relationship to Watershed Management
	DoDD 5160.63, Delegation of Authority Vested in the Secretary of Defense to Take Certain Real Property Action	• Real property actions should be made in a manner that will not result in impairments the watershed.
	DoDD4165.6, Real Property Acquisition, Management and Disposal	• Master plans should incorporate watershed management aspects, including sustainable buildings and land use. • Real property acquisition, management and disposal should be made in a manner that will not result in impairments the watershed.
	DoDD 4710.01, Archaeological and Historic Resources Management	• Watershed management activities must be consistent with the environmental, natural and cultural resources management policies.
	DoDD 6050.7, Environmental Effects Abroad of Major DoD Action	• DoD must take into account the actions of significant harm to the environment outside the US, which includes affects to water quality and watershed health.
	DoDI 4715.1, Environmental Security	• Watershed management activities must be consistent with the national security policies.
	DoDD 4700.4, Natural Resource Management Program	• Land use planning shall include natural resource preservation and conservation including watersheds and natural landscapes.
Policies and voluntary agreements	Clean Water Action Plan	• A keystone document for conducting watershed assessments, strengthening public health protections, targeting watershed protection efforts at high priority areas, controlling polluted runoff and enhancing natural resource stewardship.
	Unified Federal Policy for a Watershed Approach to Federal Land and Resource Management	• Under this agreement, DoD is committed to managing the lands, resources, and facilities as models of good stewardship and effective watershed management. This includes using a watershed approach to prevent and reduce pollution of surface and ground waters resulting from DoD land and resource management activities; and accomplish this in a unified and cost-effective manner.
	Unified Watershed Assessments	By conducting and implementing an installation watershed assessment, the installation is meeting the requirements of the UWA.
	Federal Multi-Agency Source Water Agreement	Drinking water source assessment and protection efforts will be coordinated with watershed assessments and other related CWAP action items, and measure performance of agreement implementation.

Category	Title	Relationship to Watershed Management
	Special Tributary Strategy for Federal Lands in the District of Columbia	• Reducing nutrients from entering the tributaries of Chesapeake Bay (or any water body) is an integral principle of the watershed management approach.
	Chesapeake 2000: A Watershed Partnership Agreement	• Implementing this agreement helps to improve the water quality of the Chesapeake Bay. Thus, implementation is watershed management.
	Agreement of Federal Agencies on Ecosystem Management in the Chesapeake Bay	• Implementing this agreement helps to improve the water quality of the Chesapeake Bay. Thus, implementation is watershed management.

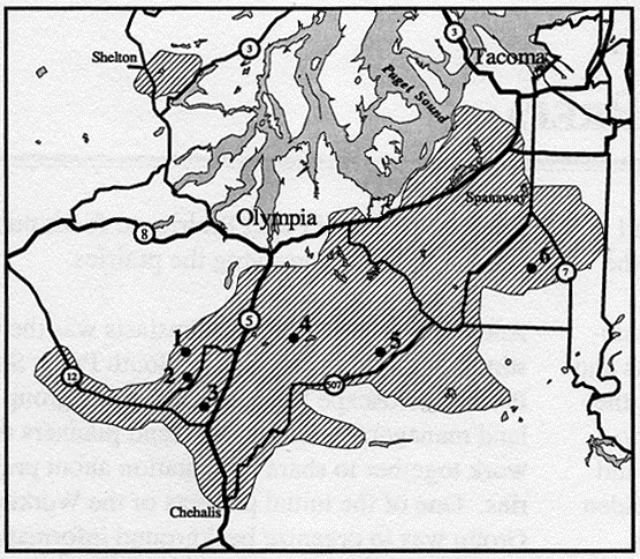
SOUTH PUGET SOUND PRAIRIES

by Kimberly Minsch, University of Washington

Introduction

South Puget Sound prairies (SPSPs) are a patchwork of grasslands, wetlands, oak woodlands, pine savannas, and open forests found on the gravelly, outwash plains of lowland Pierce and Thurston Counties (*Kruckeburg*, 1991). These prairies are flat or mounded, covered with a dense cover of grasses, moss, and lichens, and bordered by trees. Fort Lewis encompasses the largest prairies in South Puget Sound. This habitat is unlike the thick forests of western Washington because of its well-drained soils, dense grasses, groves of Oregon white oak, and patches of lodgepole and ponderosa pine. Historically, fires were used to maintain these open areas. Today, fire is generally suppressed, although land managers are once again using fire to control fast-encroaching Douglas fir and Scotch broom. Development, agriculture, weedy species, and military training activities threaten the existence of this habitat and its rare animal species. However, the U.S. Army is taking proactive measures to conserve its natural resources through programs such as the Integrated Training Area Management (ITAM) and partnerships with the Nature Conservancy and Washington Natural Heritage Program.

The largest remaining SPSPs are found on Fort Lewis (*Dorner*, 1999). Figure 1 shows the historic extent of the SPSP ecosystem and current remaining prairie areas. These are the 13th Division, Marion, Upper Weir, Lower Weir, Johnson, and the 91st Division prairies. The U.S. Army established Fort Lewis in 1916; more land was acquired and set aside during World War II. Johnson, Marion, and the 13th Division prairies were at one time settled and cultivated. Grazing continued on Fort Lewis until 1975. The primary land uses on Fort Lewis today are the cantonment, training, Gray Army Airfield, and impact areas. While some of Fort Lewis's prairies are significantly degraded, it is true that the Fort halted development when it was created (*Dorner*, 1999). Approximately 2,100 acres (17 percent) of the Fort Lewis prairies are considered intact, which is significant (*Crawford and Hall*, 1997). With a variety of challenges facing all of the prairies in South Puget Sound, there are few differences between Fort Lewis and non-military prairies (*Dorner*, 1999). Figures 2 and 3 show typical SPSP landscapes.



South Puget Sound Prairie Region, including major protected prairies. 1- Mima Mounds Natural Area Preserve, 2 - Black River - Mima Prairie- Glacial Heritage Park, 3- Scatter Creek Wildlife Area, 4 - Rocky Prairie Natural Area Preserve, 5 - Weir Prairie Research Natural Area, 6 - 13th Division Prairie Research Natural Area.

Figure 1. *Historic extent of South Puget Sound Prairie and current preserves*

Prairie Soils

The soils found on South Puget Sound prairies are gravelly, glacial outwash typical of the Spanaway series. SPSPs are located at the southern terminus of the last continental ice sheet, known as the Vashon stade (*Kruckeburg*, 1991). When the glaciers receded, cobble, gravel, and silt were washed down drainage channels and left behind. These shallow soils are very well drained and subject to drought, even though the South Puget Sound region receives more rain than Seattle and the predominately forested North Puget Sound. Streambeds are often dry during the summer.

A History of Fire

While gravelly outwash soils are certainly indicative of these prairies, their continued existence was probably due to high-frequency, low-intensity fires (*Crawford and Hall*,

1997). Fires were set by Native Americans to control the spread of Douglas fir and promote the growth of camas, which produces an edible bulb.

Figure 2. *South Puget Sound prairie landscape, showing Oregon white oak and prairie grassland*

Fauna of the South Puget Sound Prairies

A number of rare species are found on SPSPs including the western bluebird, western gray squirrel, and western pocket gopher. Nine species of reptiles, including the rare western pond turtle, and eight species of amphibians, including the rare red-legged frog, are also found on SPSPs (*Leonard and Hallock*, 1997). Forty-eight butterfly species make the prairies their home (*Dunn and Fleckenstein*, 1997).

Flora of the South Puget Sound Prairies

Douglas fir, Garry oak (uncommon), Oregon white oak, logepole pine (uncommon) and ponderosa pine are all found on SPSPs. Oregon ash, black cottonwood, big leaf maple and Oregon white oak are associated with wooded, prairie wetlands. Snowberry, red-osier dogwood, Pacific ninebark, and slough sedge are native groundcover typically found in these wetlands. Idaho fescue is the dominant prairie grass although prairie grasslands are probably better described as co-dominated by non-native species such as colonial bentgrass and velvet grass (*Chappell and Crawford*, 1997). Stands of Douglas fir have been invading the prairies for the last 150 years, most likely due to the suppression of fire.

Invasives and Noxious Weeds found on South Puget Sound Prairies

A portion (25–42%) of the vegetation on Fort Lewis's prairies are invasive species, including hairy cats' ear, silver hairgrass, St. John's Wort, and Scotch broom (*Dorner*,

1999). Noxious weeds discovered on Fort Lewis's prairies include diffuse knapweed, spotted knapweed, leafy spurge, tansy ragwort, and Canada thistle. Kentucky bluegrass now dominates the riparian corridor of Muck Creek in the 13th Division Prairie, perhaps because of the nutrients from upstream agricultural areas (*Dorner*, 1999). Reed canary grass, climbing nightshade, and purple loosestrife were also found in Fort Lewis's wetlands.

Figure 3. *South Puget Sound prairie landscape with ponderosa pine and prairie grassland.*

Integrated Training Area Management (ITAM)

Established in 1991, the Army's ITAM program incorporates a connection between training and land management, providing for environmental and natural resource protection, and supporting the training mission (see Figure 4). ITAM consists of four divisions: Land Condition Trend Analysis (LCTA), Land Rehabilitation and Maintenance (LRAM), Environmental Awareness (EA), and Training Requirements Integration (TRI). LCTA conducts studies and monitors environmental impacts. At Fort Lewis LRAM is responsible for removing Douglas fir and Scotch broom (generally with mechanical methods). The division has planted oak seedlings, as well as cottonwood, willow and Oregon ash along Muck Creek. They have installed Seibert Stakes, which designate off-limit areas, and constructed creek crossings, which are posted as Authorized Ford Crossings. EA is responsible for education of civilians and personnel. Under ITAM, vehicles are not allowed off-road within 50 m of any body of water. In addition, Fort

Lewis has a comprehensive fire management program in order to maintain open training areas and reduce fuel for accidental fires. TRI serves as a liaison unit.

Threats

"The existence of prairies and oak woodlands as well as threats to their future existence all have to do with the complex mix of geological and ecological processes, culture, climate, and economics of the Northwest." (*Ewing*, 1997)

Over 90% of Washington State's prairies have been lost in the last 150 years (*Crawford and Hall*, 1997). This is due to agricultural (30%) and urban (33%) development and the invasion by Douglas fir (32%) (*Crawford and Hall*, 1997). The invasion by weedy species, such as Scotch broom and colonial bentgrass, are damaging these prairies, too. Studies have shown that areas with evident physical disturbance (either from grazing or military training activities) are more likely to have weedy species and fewer native species of vegetation (*Dorner*, 1999).

Conservation

It is generally agreed that SPSPs are a unique habitat and worth preserving. The following conservation measures are repeated throughout the literature.

- Remaining natural areas should be protected from development and physical disturbance.
- The spread of Douglas fir and Scotch Broom should be controlled with three- to five-year rotation of prescribed burns (*Tveten*, 1997).
- Weedy species should also be controlled and native vegetation should be replanted.
- With careful management, these unique habitats can be preserved.

Figure 4. *South Puget Sound prairie landscape with military operations.*

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WATER QUALITY REPORT FOR CLOVER AND MOREY CREEKS ON MCCHORD AIR FORCE BASE

by 2nd LT Katherine Dehne, University of Washington

Abstract

In response to the growing concern regarding its impact on the water quality of Clover Creek, McChord Air Force Base began a monitoring program. The purpose of this study is to analyze the data that has been collected over the past five years and make recommendations for improvements to the monitoring program. There is a special focus on nutrients levels including nitrate and phosphate since Lake Steilacoom, which eventually receives the water, has had algal bloom problems associated with eutrophication. The conclusions drawn from the data collected by the Air Force from March 1995 through January 2000 and additional stream observations are: (1) in general, nitrate concentrations increase slightly as the creek flows through the base, (2) phosphate concentrations do not increase as the creek flows from inlet to outlet, (3) dissolved oxygen data is insufficient, (4) temperature and pH readings are within Washington State water quality standards, and (5) testing for phenol, oil and grease, and metals has some value for monitoring efforts. Recommendations for improving the monitoring program include creating a comprehensive binder that includes specific goals: where, what, and when to monitor; training for sampling personnel; using standard methods for sampling techniques; and setting up a better database that is reviewed as the data is received. These changes will add credibility to the monitoring program and enhance its value to McChord Air Force Base.

Figure 1. *Clover Creek inlet with airfield in background.*

Introduction

Urban areas and military installations can have much land covered by impervious surfaces, like runways and parking lots (Figure 1). This causes run-off to be more pronounced and concentrated. Erosion can become a problem in the stream channel and on the banks, increasing the concentration of pollutants going directly to the stream instead of being filtered by the soil or absorbed by the plants.

Some streams act as the main receiving body for stormwater run-off. Ensuring that the stream remains healthy is important to those that enjoy the stream, use the stream, live in and around the stream, and receive the stream. A receiving lake is susceptible to pollutants (both nutrient and toxic) that come into the system from the feeding streams.

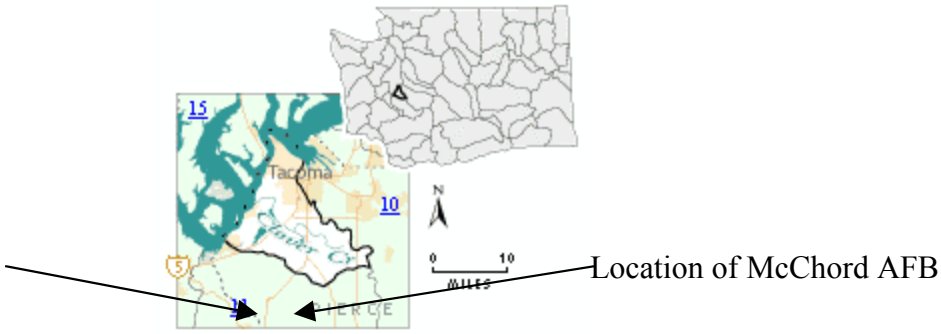

Figure 2. *Map of Water Resource Inventory Area 12.*

Background on McChord Creeks

McChord Air Force Base is located in Tacoma, WA within the Water Resource Inventory Area (WRIA) 12 (Figure 2). Morey Creek and Clover Creek enter McChord AFB on the eastern boundary of the base and flow east to west for less than 2 miles across the base as they form one stream, Clover Creek. This stream was relocated in the late 1930s from its natural channel to make room for the airfield. It also runs underground in two corrugated steel pipes for a small portion while on base. The creek contains native cutthroat trout. In addition, before Morey Creek merges with Clover Creek, a concrete dam forms a small pond.

Clover Creek originates from Spanaway Lake located to the southeast of the base. This lake is shallow and has eutrophication problems. The springs that feed the lake are high in phosphates.

The combined stream is classified as Class A–Excellent (*IAW Chapter 173-201A*). The stream meets that following requirements: dissolved oxygen concentration, > 8.0 mg/L; temperature, may not exceed 18°C due to human activities; pH, 6.5–8.5; turbidity, < 5 NTU + background (when background <50 NTU); aesthetic values, no unnatural suspended, floating, or submerged matter.

The waters evaluated here flow from a residential area before entering the base and exit into a commercial and residential area. Overall, WRIA 12 is classified as urban. Eventually the creek flows into Steilacoom Lake in the city of Lakewood. Monitoring the creek is important since Steilacoom Lake contains algal blooms. These are suspected to occur due to high concentrations

of phosphate and low concentrations of nitrate. This allows cyanobacteria to out-compete other algae and bacteria.

McChord AFB is an easily identifiable and regulated contributor to the creek due to the extensive documented stormwater system it manages and its high profile mission. Due to these aspects, McChord AFB is often the recipient of complaints and needs the ability to assess their impacts on the stream in a reliable, reproducible manner.

Regulatory Environment for Clover Creek

Clover Creek and Morey Creek receive the stormwater run-off from the base. Stormwater discharges are regulated under the nation-wide EPA General Stormwater Permit and are specified in federal regulations (NPDES permit number: WA-002510-1 issued by the EPA on 11 Feb 1975). An important item of the permit is preparation of a stormwater management plan. The plan for McChord AFB requires analysis of the stormwater utility system; committee meetings are held and visual inspections are made of the outfalls received by Clover Creek. The Chief of the Environmental Flight at McChord AFB reports that the strictest requirement in the program is visual monitoring of the stream on a quarterly basis. During a visual inspection the observer looks to see if there is an oily sheen visible or any other change in the nature of the water. Testing for traces of dissolved chemicals is not done.

In addition to the visual inspections, every major outfall to Clover Creek runs through an oil/water separator. This process removes oily sheens from the top one to two inches of stormwater. The stream receives no industrial discharges. Any water that may pose a risk is plumbed to the sanitary sewer system and treated at Fort Lewis, Washington.

Original Monitoring Goals

In response to community inquiries about stream water quality, McChord AFB started voluntary monitoring. The public's claim that McChord AFB was seriously polluting Clover Creek led to the decision to start collecting data where the stream enters the base and where it exits the base. This database was intended to support any position McChord AFB would take with respect to water quality in Clover Creek for the portion that flows through McChord AFB. Especially important is the data collected on phosphate and nitrate concentrations due to the receiving lake having algal bloom problems.

Nutrients and Eutrophication

Eutrophication was originally a term used to describe the natural aging process of a lake as it is transformed from lake to marsh to meadow (*Chapra*, 1997). Normally this process takes thousands of years but it can be accelerated by excess nutrients from human activities such as fertilizing crops and detergent use. The process is sometimes called cultural eutrophication.

Certain levels of nutrients are needed for growth of plants and animals. Nitrogen and phosphorus are two essential and controllable nutrients. Nitrogen is present in four primary forms: free nitrogen (N_2), ammonium (NH_4^+)/ammonia (NH_3), nitrite (NO_2^-)/nitrate (NO_3^-), and organic nitrogen (*Chapra*, 1997). Phytoplankton and fixed plants can utilize both ammonia and nitrate, aerobic bacteria can oxidize ammonia and nitrite to nitrate (nitrification), free nitrogen can be utilized by nitrogen-fixing algae and bacteria, and organic nitrogen decomposes to ammonia. These interconnected cycles are important for understanding nitrogen as a nutrient. Nitrate as a pollutant occurs when the concentration of nitrate gets too high, usually due to agricultural fertilizers.

Phosphate is important to monitor because it is usually in short supply relative to other nutrients. Phosphate is part of the soluble reactive phosphorus group also called orthophosphate and is readily available to plants (*Chapra*, 1997). It can be derived from many sources. Particulate organic phosphorus that includes living plants, animals, bacteria, and organic detritus forms nonparticulate unavailable organic phosphorus that then becomes the phosphate available to plants. Human and animal wastes both contain substantial amounts of phosphate. In addition, fertilizers and detergents also contribute to natural water concentration increases.

Washington State surface water quality standards do not address specific nitrate and phosphate concentrations because they vary depending on the water body. Water clarity, pH, dissolved oxygen (DO), and specie composition are analyzed instead.

Data from Present Monitoring Program

Grab samples were made from March 1995 to January 2000. The samples for metal analysis were preserved in nitric acid and sent to Brooks AFB, TX. The results are recorded and kept by the Bioenvironmental Engineering Services on base. The rest of the samples were sent to Water Management Laboratories in Tacoma, WA and use the EPA method 1664 N-Hexane Extractable Material (HEM) analysis.

The data points available are difficult to compare and analyze due to gaps in the data and the lack of stream flow data. Even though there is a log for stream flow data kept with the other data, no observations have been made. Flows are important in order to perform a mass balance to better determine the affect McChord AFB has on the streams.

Nitrate

By assuming that the flows from the two inlets are somewhat equal, the average of the two concentrations can be compared to the Clover Creek outflow from McChord AFB.

Table 2. *McChord AFB stream monitoring data—nitrate (mg/L)*

DATE	CCI	MCI	Average	CCO	Change	
3/24/1995	1.96	1.8	1.88	1.8	-0.08	Decrease
6/8/1995	1.22	1.34	1.28	1.6	0.32	Increase
7/26/1995	0.59	0.78	0.685	0.94	0.26	Increase
11/7/1995	0.82	0.56	0.69	0.44	-0.25	Decrease
1/29/1996	1.3	2.12	1.71	1.9	0.19	Increase
4/8/1996	1.48	1.38	1.43	1.38	-0.05	Decrease
7/17/1996	0.68	0.97	0.825	1.15	0.33	Increase
10/7/1996	0.56	0.8	0.68	1.32	0.64	Increase
1/29/1997	1.58	1.8	1.69	2.08	0.39	Increase
4/9/1997	1.26	1.32	1.29	1.35	0.06	Increase
7/2/1997	0.35	0.68	0.515	0.75	0.24	Increase
10/13/1997	0.38	0.56	0.47	0.56	0.09	Increase
1/14/1998	1.2	1.36	1.28	1.34	0.06	Increase
4/8/1998	1.28	1.3	1.29	1.26	-0.03	Decrease
10/14/1998	0.32	0.52	0.42	0.68	0.26	Increase
3/19/1999	1.7		1.7	1.8	0.10	Increase
4/21/1999	1.4	1.4	1.4	1.5	0.10	Increase
7/29/1999	0.8	1.2	1	1.2	0.20	Increase
10/15/1999		0.03	0.03	0.05	0.02	Increase
1/12/2000	1.3	1.5	1.4	1.4	0.00	No Change

Note: CCI, Clover Creek inlet; MCI, Morey Creek inlet, CCO, Clover Creek outlet

It appears from this data that McChord AFB does have a slight effect on the nitrate concentration as the creeks flow from inlets to outlet. The reason for this increase could come from a variety of natural sources not related to military activities on the base. There are a significant number of waterfowl (Figure 3) that make the creek a resting spot. There is ample vegetation degrading that could be adding to the nitrogen concentration. More water quality data, like DO, must be collected before determining where the minute addition of nitrate originates.

Figure 3. *Clover Creek outlet showing waterfowl and the permanent barrier used to prevent any accidental oil spills from McChord AFB going off base*.

In the winter and spring the nitrate concentrations are generally higher than the summer and fall (Figure 4). This seasonal variation could be due to many things. One hypothesis is that the plant uptake of nitrate during the warmer summer and fall months is greater due to their productivity level and this may decrease the nitrate concentration. More oxygen may be available in the water during the cooler seasons, and thus oxidation to nitrate during the winter and spring increases the nitrate concentration. Increased precipitation in the winter and spring could increase the run-off to the creek and pick up nutrients that had been dry and immobile during the drier seasons. Migration of waterfowl may also play a role in the variation.

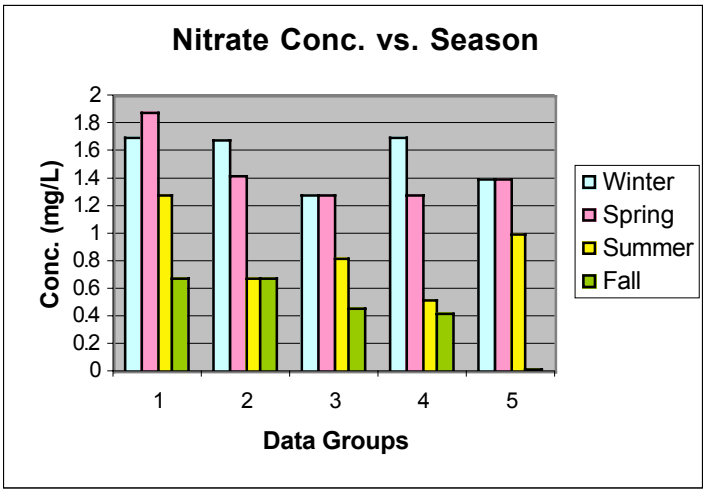

Figure 4. *Seasonal analysis of nitrate concentration*

Phosphate

Phosphate data points were consistently <0.1 mg/L. A test is needed that can detect concentrations to values of .01 accuracy.

Table 3. *McChord AFB stream monitoring data—phosphate (mg/L)*

DATE	CCI	MCI	Average	CCO	Change	
3/24/1995	< 0.1	< 0.1	< 0.1	< 0.1	0	No Change
6/8/1995	< 0.1	< 0.1	< 0.1	< 0.1	0	No Change
7/26/1995	< 0.1	< 0.1	<0.1	< 0.1	0	No Change
11/7/1995	< 0.1	< 0.1	<0.1	< 0.1	0	No Change
1/29/1996	0.013	< 0.11	0.0615	0.11	0.049	Increase
4/8/1996	< 0.1	< 0.1	<0.1	< 0.1	0	No Change
7/17/1996	< 0.1	< 0.1	<0.1	< 0.1	0	No Change
10/7/1996	< 0.1	< 0.1	<0.1	0.2	>.1	Increase
1/29/1997	< 0.1	< 0.1	<0.1	< 0.1	0	No Change
4/9/1997	<0.1	<0.1	<0.1	<0.1	0	No Change
7/2/1997	<0.1	<0.1	<0.1	<0.1	0	No Change
10/13/1997	< 0.1	< 0.1	<0.1	< 0.1	0	No Change
1/14/1998	< 0.1	< 0.1	<0.1	<0.1	0	No Change
4/8/1998	<0.1	<0.1	<0.1	<0.1	0	No Change
10/14/1998	0.27	0.03	0.15	0.02	-0.1	Decrease
3/19/1999	0.02		0.01	0.02	0.01	Increase
4/21/1999	0.03	<0.01	0.02	0.01	0.01	Decrease
7/29/1999	0.03	0.06	0.045	0.03	-0.015	Decrease
10/15/1999	no outfall	<1	1	1	0	No Change
1/12/2000	0.03	0.02	0.025	0.06	0.035	Increase

Note: CCI, Clover Creek inlet; MCI, Morey Creek inlet, CCO, Clover Creek outlet

It is difficult to draw conclusions from this data. It appears there is no change in phosphate concentration in the creek as it flows through McChord AFB.

Dissolved Oxygen

Given the few data points provided, dissolved oxygen is very low and does not meet the Washington State water quality standards. It is doubtful that these numbers are accurate. This data stopped being collected after 1996 with no explanation. Since it is a very important parameter for monitoring stream health, it should be reinstated. A different method should be employed so that accurate numbers can be collected, since these are unreasonably low.

Table 4. *McChord AFB stream monitoring data—dissolved oxygen (mg/L)*

Date	CCI	MCI	CCO
3/24/1995	1	1	1
6/8/1995	1	1	1
7/26/1995	0.8	0.8	0.8
11/7/1995	1	1	1
1/29/1996	1	1	1

Temperature

Temperature data collected is reasonable and is above water quality standards only at a few times between 1995 and 1999 (<18°C). It appears that these high temperatures are not due to human influences since inlets are as high as the outlet. There are blanks in the data set on the same day. A quality check on the data at the time of report would have caught these errors.

Table 5. *McChord AFB stream monitoring data—temperature (ºC)*

Date	CCI	Date	MCI	Date	CCO
3/24/1995	15	3/24/1995	15	3/24/1995	15
6/8/1995	19	6/8/1995	18	6/8/1995	16
7/26/1995	19	7/27/1995	19	7/26/1995	19
11/7/1995	4	11/7/1995	4	11/7/1995	5
1/29/1996	4.2	1/29/1996	4	1/29/1996	5.5
4/8/1996	11	4/8/1996	9	4/8/1996	10
7/17/1996	15	7/17/1996	15	7/17/1996	14
10/7/1996	14	10/7/1996	13	10/7/1996	12
1/29/1997	5.5	1/29/1997	6	1/29/1997	6
4/9/1997	11	4/9/1997	12	4/9/1997	12
7/2/1997	15	7/2/1997	17	7/2/1997	15
10/13/1997	14	10/13/1997	4	10/13/1997	12
1/14/1998	4	1/14/1998	9	1/14/1998	4
4/8/1998	10	4/8/1998	14	4/8/1998	12
7/28/1998		7/28/1998		7/28/1998	
10/14/1998	9	10/14/1998	12	10/14/1998	11
1/28/1999		1/28/1999		1/28/1999	

pH

The method for pH analysis was not included in the data set. The data provided for pH, however, are reasonable and only slightly lie outside the water quality standards at a few points (6.5-8.5). pH is simple to monitor due to the ease of tests available. All of the outflow pH values are within water quality limits.

Table 6. *McChord AFB stream monitoring data—pH*

Date	CCI	Date	MCI	Date	CCO
3/24/1995	7.3	3/24/1995	7.1	3/24/1995	7.2
6/8/1995	7	6/8/1995	7	6/8/1995	7.3
7/26/1995	7.3	7/27/1995	7.1	7/26/1995	7.2
11/7/1995	7.1	11/7/1995	7	11/7/1995	7
1/29/1996	7.9	1/29/1996	7.9	1/29/1996	7.9
4/8/1996	7.4	4/8/1996	7.2	4/8/1996	7.3
7/17/1996	7.1	7/17/1996	7.1	7/17/1996	7.1
10/7/1996	7.1	10/7/1996	7.2	10/7/1996	7.3
1/29/1997	7.2	1/29/1997	7.1	1/29/1997	7.3
4/9/1997	7.2	4/9/1997	7.2	4/9/1997	7.3
7/2/1997	6.7	7/2/1997	7.1	7/2/1997	6.7
10/13/1997	6.6	10/13/1997	7.2	10/13/1997	7.1
1/14/1998	6.9	1/14/1998	7	1/14/1998	7
4/8/1998	7.2	4/8/1998	6.9	4/8/1998	6.9
7/28/1998		7/28/1998		7/28/1998	
10/14/1998	7.2	10/14/1998	7.2	10/14/1998	6.7
1/28/1999		1/28/1999		1/28/1999	
4/21/1999		4/21/1999		4/21/1999	
7/29/1999	6.4	7/29/1999	7.14	7/29/1999	6.8
7/29/1999	6.4	7/29/1999	7.14	7/29/1999	6.8
7/29/1999	6.4	7/29/1999	7.14	7/29/1999	6.8
7/29/1999	6.4	7/29/1999	7.14	7/29/1999	6.8
10/15/1999		10/15/1999		10/15/1999	6.7
10/20/1999		10/20/1999		10/20/1999	6.7
1/12/2000	6.6	1/12/2000	6.4	1/12/2000	6.8

Other Data

Other data collected include values for oils and grease, phenols, lead, mercury, and silver. It is important for McChord AFB to continue monitoring these due the activities performed on the base. These items are important from a toxic and environmental hazard perspective.

Table 7. *McChord AFB stream monitoring data—phenol (mg/L)*

Date	CCI	Date	MCI	Date	CCO
3/24/1995	< 10	3/24/1995	< 10	3/24/1995	< 10
6/8/1995	< 10	6/8/1995	15	6/8/1995	< 10
7/26/1995	< 10	7/27/1995	< 10	7/26/1995	30
11/7/1995	10	11/7/1995	21	11/7/1995	56
1/29/1996	< 10	1/29/1996	< 10	1/29/1996	< 10
4/8/1996	27	4/8/1996	< 10	4/8/1996	< 10
7/17/1996	< 10	7/17/1996	< 10	7/17/1996	< 10
10/7/1996	< 10	10/7/1996	< 10	10/7/1996	< 10
1/29/1997	< 10	1/29/1997	< 10	1/29/1997	< 10
4/9/1997	<10	4/9/1997	<10	4/9/1997	<10
7/2/1997	<10	7/2/1997	<10	7/2/1997	<10
10/13/1997	<10	10/13/1997	< 10	10/13/1997	< 10
1/14/1998	<10	1/14/1998	< 10	1/14/1998	<10
4/8/1998	<10	4/8/1998	< 10	4/8/1998	<10
7/28/1998		7/28/1998		7/28/1998	
10/14/1998	<0.005	10/14/1998	<0.005	10/14/1998	<0.005
1/28/1999	<0.005	1/28/1999	<0.005	1/28/1999	<0.005
4/21/1999	<0.1	4/21/1999	<0.1	4/21/1999	0.1
4/21/1999		4/21/1999		4/21/1999	
7/29/1999	<0.1	7/29/1999	0.1	7/29/1999	<0.1
7/29/1999		7/29/1999		7/29/1999	
10/15/1999		10/20/1999		10/15/1999	
1/12/2000		10/15/1999		10/20/1999	
1/12/2000	<0.1	1/12/2000	<0.1	1/12/2000	<0.1

The phenol concentrations vary widely from 1995 to 2000. There was perhaps a change made in the sampling or analyzing techniques. A quality check on the data at the time of report would have caught these discrepancies.

Oil and Grease

Oil and grease find their way into waterways rather easily with help from precipitation. There are, however, quality problems with this data. Clover Creek inlet, and Morey Creek inlet and outlet all have very high concentrations in November 1995 compared with the rest of the data set. The outlet value for January 1997 should have also raised concern. These reports could be the result of inaccurate sampling.

Table 8. *McChord AFB stream monitoring data—oil and grease (mg/L)*

Date	CCI	Date	MCI	Date	CCO
3/24/1995	1.7	3/24/1995	0.3	3/24/1995	0.8
6/8/1995	0.6	6/8/1995	1	6/8/1995	0.3
7/26/1995	1.68	7/27/1995	0.3	7/26/1995	0.68
11/7/1995	7.36	11/7/1995	9.12	11/7/1995	4.8
1/29/1996	0.4	1/29/1996	0.4	1/29/1996	0.4
4/8/1996	0.6	4/8/1996	0.6	4/8/1996	0.3
7/17/1996	0.32	7/17/1996	1.84	7/17/1996	0.3
10/7/1996	0.64	10/7/1996	0.3	10/7/1996	0.32
1/29/1997	0.64	1/29/1997	0.48	1/29/1997	6.16
4/9/1997	<0.3	4/9/1997	BIT	4/9/1997	<0.3
7/2/1997	0.34	4/29/1997	<0.3	7/2/1997	<0.3
10/13/1997	0.31	7/2/1997	<0.3	10/13/1997	<0.3
1/14/1998	0.4	10/13/1997	0.4	1/14/1998	0.3
4/8/1998	0.5	1/14/1998	<0.3	4/8/1998	0.4
7/28/1998		4/8/1998	<0.3	7/28/1998	
10/14/1998	<5	7/28/1998		10/14/1998	<5
1/28/1999	<1	10/14/1998	<5	1/28/1999	<1
3/19/1999		1/28/1999	<1	3/19/1999	
4/21/1999		4/21/1999		4/21/1999	
4/21/1999	<1	4/21/1999	<1	4/21/1999	<1
7/29/1999	<1	7/29/1999	<1	7/29/1999	<1
7/29/1999		7/29/1999		10/15/1999	1.7
10/15/1999		10/20/1999		10/15/1999	1.7
1/12/2000		10/15/1999	1.2	10/20/1999	
1/12/2000	<0.1	1/12/2000	<1	1/12/2000	<1

Miscellaneous

Table 9 reports concentrations of heavy metals. Concentrations reported are very low and seem to have no increase as the stream flows through the base.

Table 9. *McChord AFB stream monitoring data—lead, mercury, and silver (mg/L)*

Clover Creek Inlet				**Morey Creek Inlet**				**Clover Creek Outlet**			
DATE	LEAD	MERCURY	SILVER	DATE	LEAD	MERCURY	SILVER	DATE	LEAD	MERCURY	SILVER
3/24/1995	< 0.02	< 0.0002	< 0.01	3/24/1995	< 0.02	< 0.0002	< 0.01	3/24/1995	< 0.02	< 0.02	< 0.01
6/8/1995	< 0.02	< 0.0002	< 0.01	6/8/1995	< 0.02	< 0.0002	< 0.01	6/8/1995	< 0.02	< 0.02	< 0.01
7/26/1995	< 0.02	< 0.0002	< 0.01	7/27/1995	< 0.02	< 0.0002	< 0.01	7/26/1995	< 0.02	< 0.02	< 0.01
11/7/1995	< 0.02	< 0.0002	< 0.01	11/7/1995	< 0.02	< 0.0002	< 0.01	11/7/1995	< 0.02	< 0.02	< 0.01
1/29/1996	< 0.02	< 0.0002	< 0.01	1/29/1996	< 0.02	< 0.0002	< 0.01	1/29/1996	< 0.02	< 0.0002	< 0.01
4/8/1996	< 0.02	< 0.0002	< 0.01	4/8/1996	< 0.02	< 0.0002	< 0.01	4/8/1996	< 0.02	< 0.0002	< 0.01
7/17/1996	< 0.02	< 0.0002	< 0.01	7/17/1996	< 0.02	< 0.0002	< 0.01	7/17/1996	< 0.02	< 0.0002	< 0.01
10/7/1996	< 0.02	< 0.0002	< 0.01	10/7/1996	< 0.01	< 0.0002	< 0.01	10/7/1996	< 0.02	< 0.0002	< 0.01
1/29/1997	< 0.02	< 0.0002	< 0.01	1/29/1997	< 0.01	< 0.0002	< 0.01	1/29/1997	< 0.02	< 0.0002	< 0.01
4/9/1997	<0.02	<0.0002	<0.01	4/9/1997	<0.02	<0.0002	<0.01	4/9/1997	<0.02	<0.0002	<0.01
7/2/1997	<0.02	<0.0002	<0.01	4/29/1997				7/2/1997	<0.02	<0.0002	<0.01
10/13/1997	<0.02	<0.0002	<0.01	7/2/1997	<0.02	<0.0002	<0.01	10/13/1997	< 0.02	< 0.0002	< 0.01
1/14/1998	<0.02	<0.0002	<0.01	10/13/1997	< 0.02	< 0.0002	< 0.01	1/14/1998	<0.02	<0.0002	<0.01
4/8/1998	<0.02	<0.0002	<0.01	1/14/1998	< 0.01	< 0.0002	< 0.01	4/8/1998	<0.02	<0.0002	<0.01
7/28/1998				4/8/1998	< 0.01	< 0.0002	< 0.01	7/28/1998			
10/14/1998	0.017	<0.0002	<0.002	7/28/1998				10/14/1998	<0.01	<0.0002	<0.002
1/28/1999				10/14/1998	<0.01	0.00169	<0.002	1/28/1999			
3/19/1999				1/28/1999	<0.010	0.0002	<0.002	3/19/1999			
4/21/1999				4/21/1999				4/21/1999			
4/21/1999				4/21/1999				4/21/1999			
4/21/1999	<0.010	<0.0002	<0.0020	4/21/1999	<0.010	0.0002	<0.002	4/21/1999	<0.010	<0.0002	<0.0020
7/29/1999				7/29/1999				7/29/1999			
7/29/1999				7/29/1999				7/29/1999			
7/29/1999				7/29/1999	<0.010	<0.00020	<0.0020	7/29/1999	<0.010	<0.0002	<0.0020
7/29/1999	<0.010	<0.0002	<0.0020	10/20/1999	<0.01	<0.0002	<0.0020	10/15/1999			
10/15/1999				10/15/1999				10/20/1999	<0.01	<0.0020	<0.0020
1/12/2000	<0.010	<0.0002	<0.002	1/12/2000	<0.01	<0.0002	<0.002	1/12/2000	<0.01	<0.002	<0.002
1/12/2000				1/12/2000				1/12/2000			

Monitoring Program Recommendations

Until recently no TMDLs (total maximum daily loads) had been determined for this stretch of Clover Creek even though other segments have problems with DO, temperature, and fecal coliform bacteria. There is now a phosphate loading concern for the creek so improvement to the monitoring program is desired. There are six steps for program improvement.

1. Outlining goals of the program: Possible goals are (1) screening for potential pollution problems, (2) determining the influence McChord AFB has on the pollution of the stream and (3) monitoring the overall health of the stream.

2. Identifying what and where to monitor: Determine what aspects of water quality and stream characteristics to focus on for the monitoring program. Below are the items recommended for this project and reasons for monitoring them.

- Water temperature: Important for water quality analysis and also meeting the Class A Stream requirements.
- pH: One of the most important aspects of water chemistry and there is also a standard for Class A streams.
- Dissolved oxygen: A good indicator of health for streams and is needed for aquatic life to thrive in addition to meeting the water quality standard.
- Nitrate: An essential nutrient that needs to be monitored to ensure that high concentrations do not exist and enhance eutrophication downstream.
- Phosphorus (phosphate or orthophosphates): An essential nutrient that is of utmost important in this program due to the downstream lake cyanobateria blooms.
- Phenol: Can be present in industrial areas and react with oxidizing agents to produce odors.
- Oils and grease: May cause surface films and affect aerobic and anaerobic biological processes.
- Metals (lead, mercury, and silver): Heavy metals are toxic and are cause for concern if found in certain concentrations in aquatic environments.
- Flow: It is beneficial to know the flow when doing analysis of two streams converging into one to aid modeling efforts.
- Fish: If fish continue to thrive in the stream it is a good indicator that the stream is healthy.
- Photographic surveys: Pictures convey a message more easily and with detail to the public.

The location of the sampling can continue to be at the two stream inlets and at the one outlet from the base since these three data points will satisfy the goals. However, additional data can be collected upstream and downstream of the four major storm drain outfalls to better monitor the contributions McChord AFB makes to the streams. At these additional locations, all items do not need to be monitored but testing for pH, temperature, DO, nitrate, and phosphorus would be most advantageous for the monitoring program.

3. Determining the frequency and timing of sampling: It is recommended that chemical monitoring occur monthly and biological assessments occur biannually. Due to cost constraints and the nature of this volunteer monitoring effort, the quarterly sampling can continue for McChord AFB. Flow data should be collected each time chemical samples are taken. Samples should be taken at the same time of the month and day to ensure that biological influence on nutrient levels and DO are consistent throughout the data set.

4. Training for samplers: A brief description should be included of how the samplers are trained for the program. For example, a checklist can be made that identifies that an individual knows the proper way to prepare the sample container, take a sample, preserve a sample if necessary, use the pH or DO probes, read the thermometer accurately, etc. The person supervising the training can come from an accredited lab or governmental agency such as the Department of Ecology (DOE) or the Environmental Protection Agency (EPA).

5. Using standard methods for sampling and analysis: Using standard methods that are approved by the EPA add credibility to the monitoring program. The methods that are recommended for this program are gathered from *Standard Methods for the Examination of Water and Wastewater*, 19th ed. (*Eaton et al*., 1995).

Tabel 10. *Summary of standard methods for sampling water and wastewater* (*Eaton et al*., 1995)

Item of Interest	Container for Sampling	Minimum Size of Sample	Grab or Continuous	Preservation Technique	Max Time Stored (Recommended/Required by EPA)
Nitrate	Plastic, Glass	100 mL	Grab[3]	Analyze ASAP or refrigerate	48 hr/ 48 hr
Phosphorous	Glass (A)[1]	100 mL	Grab	Refrigerate	48 hr/ Not specified
DO	G	300 mL	Grab	Analyze ASAP	.5 hr/ immediate
PH	P, G	50 mL	Grab	Analyze ASAP	2 hr/ immediate
Temperature	P, G	--	Grab	Analyze ASAP	immediate/immediate
Phenols	P, G	500 mL	Grab	Ref., add H_2SO_4 to pH<2	--/28 days
Oils and Grease	Glass [2]	1000 mL	Grab	Add HCl to pH <2, ref.	28 days/28 days
Lead	P (A), G(A)	500 mL	Grab	Add HNO_3 to pH <2, ref.	28 days/28 days
Mercury	P (A), G(A)	500 mL	Grab	Same as above	28 days/28 days
Silver	P (A), G(A)	500 mL	Grab	Same as above	28 days/28 days

[1] (A) denotes the need to rinse container with 1 + 1 HNO_3 solution

[2] This container needs to be a wide mouth calibrated container

[3] Grab samples can be used for each of the items in the table. When a source is known to be relatively constant in composition, a sample taken at one point at a certain time can represent a longer time period and larger volume.

Dissolved oxygen, pH, and temperature samples can be tested in the field by the trained personnel. All other samples should be preserved and sent to an accredited lab in the area. A state accredited lab can be found though WAC 173-050 or Ecology Executive Policy 1-22.

6. A data review plan: Reviewing data collected is another important aspect. Field sheets and lab data sheets should be checked for completeness, data should be screened for outliers, and a database should be developed or adapted to store and manipulate the data. A disk is provided as well as a print out of a sample sheet for storing the data. The elements of such a database should be clearly explained in order to allow users to interpret the data accurately and with confidence.

Continuing Efforts:

The planting of alders along the stream bank should be continued. This will help with erosion, nitrogen levels, shading, and overall health of the water. Poplars can also be used for this purpose with the added benefit of phyto-remediation for some toxic pollutants. Poplars also slow toxic water plums that may become a problem in the future.

Conclusion

Clover Creek and Morey Creek, which flow onto McChord Air Force Base, must be monitored. This is done to provide substantiation that the Air Force Base does or does not have a detrimental effect on the streams as they flow through the base. Past data collection efforts show that nitrate concentrations increased slightly as the stream flowed through the base and phosphate concentrations did not change. McChord AFB does not detrimentally impact nutrient levels in the stream. By adapting the recommendations provided here, McChord AFB will improve its quality-monitoring program. The stream is currently healthy on the base and will continue to be so with an effective monitoring program and other efforts by the Air Force.

Acknowledgements

Dr. John Ferguson, University of Washington; Dr. John Yersley; Mike Grenko, Head of the Environmental Flight at McChord AFB; Maj. James Rypkema, USAF, BSC, CIH, Chief of Bioenvironmental Engineering at McChord AFB; A1C Elaine Strona; Sgt. Shawn Petro; Dr. Mike Brett, University of Washington; Stephen Chapel, City of Lakewood Associate Civil Engineer; Lt. Heidi Potter.

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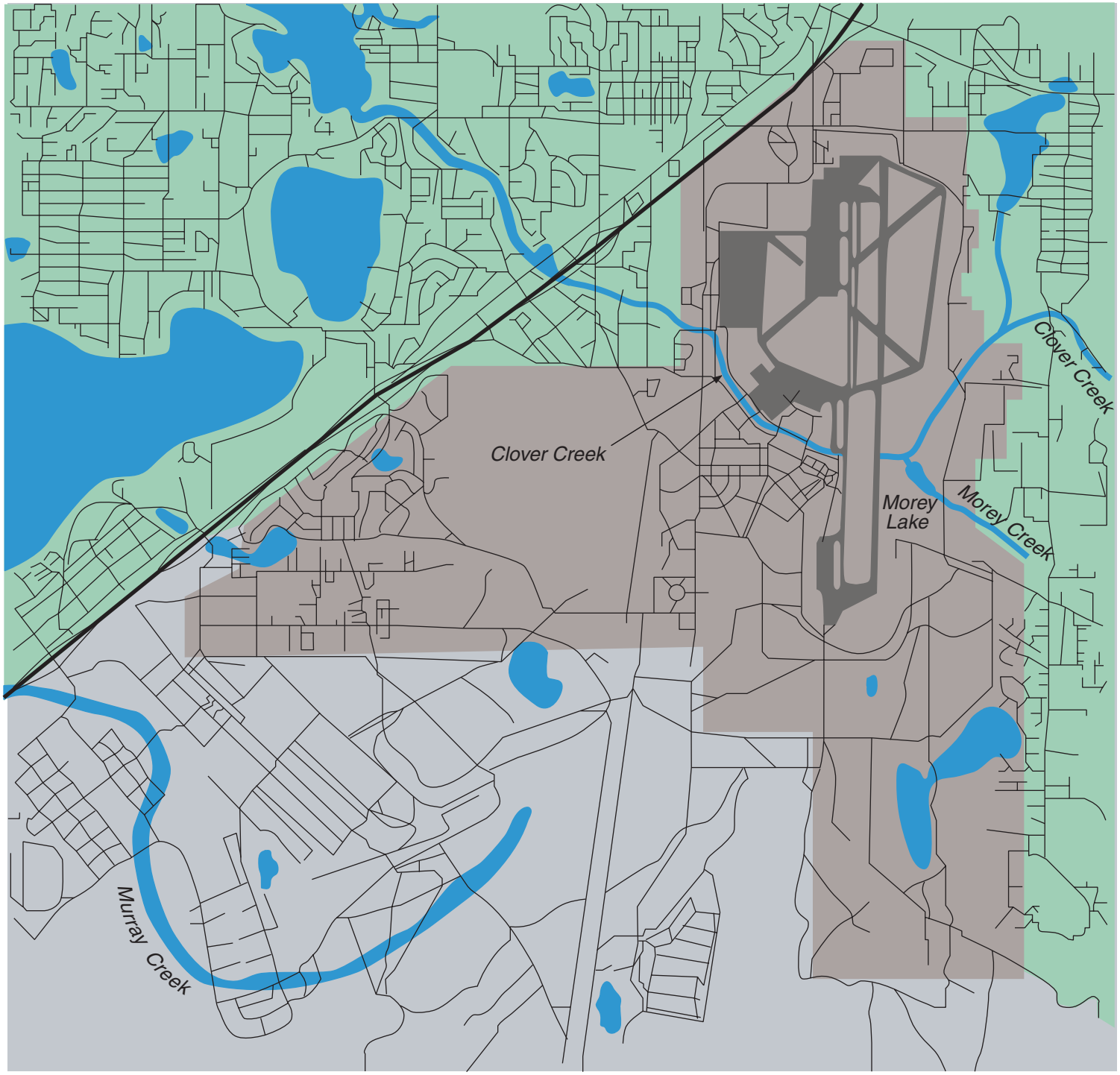
McChord Air Force Base
Clover Creek
Base Map



LEGEND

- McChord AFB
- Flight Operations Area (Runway)
- Ft. Lewis Army Base
- Off Base
- Streams, lakes and wetlands
- Roads

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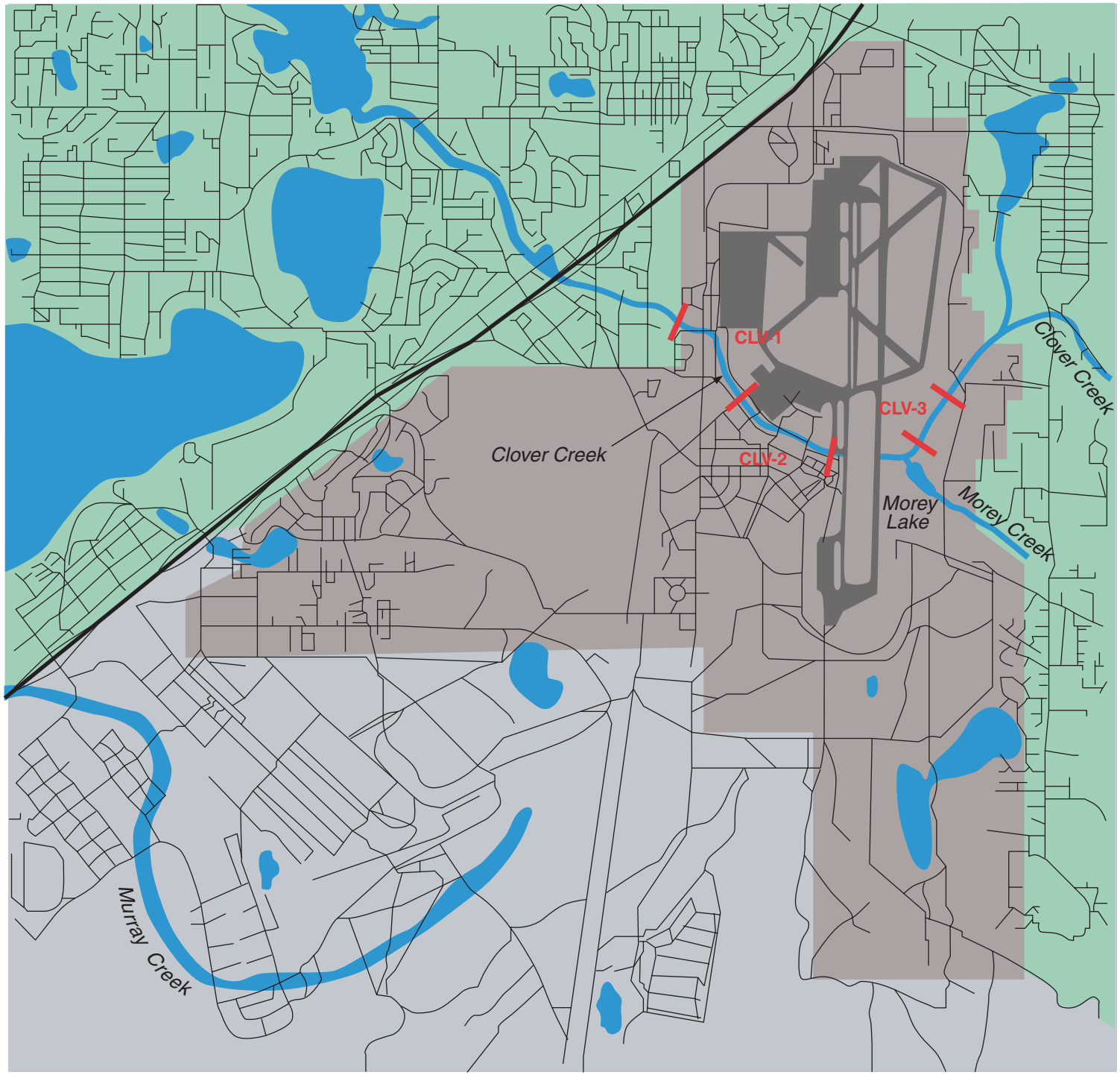
miles

Map F-1

McChord Air Force Base
Clover Creek
Stream Survey Reach Map



LEGEND

- McChord AFB
- Flight Operations Area (Runway)
- Ft. Lewis Army Base
- Off Base
- Streams, lakes and wetlands
- Roads
- Survey reach location (CLV-1)

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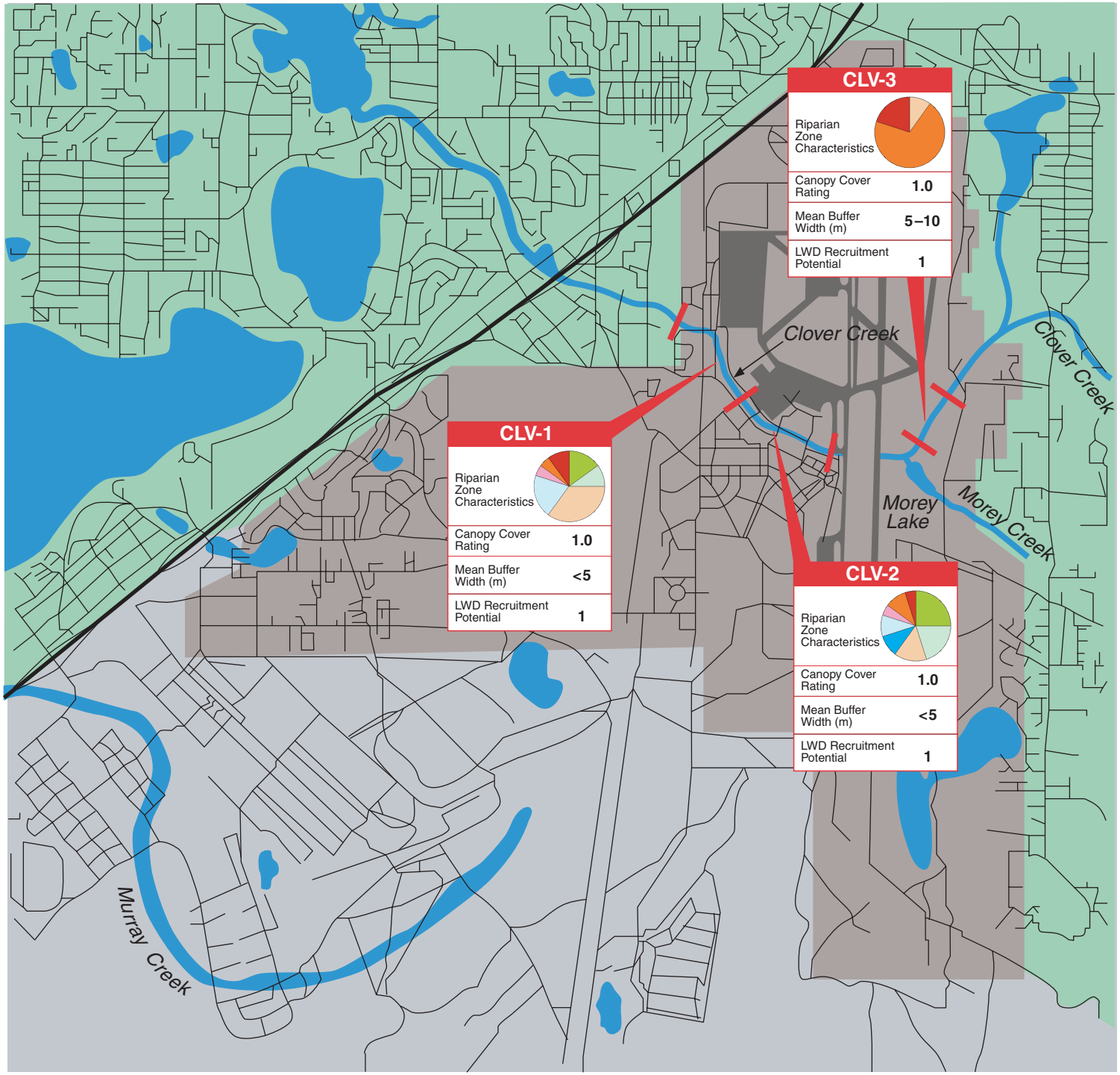
miles

McChord Air Force Base
Clover Creek
Riparian Conditions Map



LEGEND

- McChord AFB
- Flight Operations Area (Runway)
- Ft. Lewis Army Base
- Off Base
- Streams, lakes and wetlands
- Roads
- CLV-1 Survey reach location
- CLV-3 *See Map Legend F-9 for explanation*

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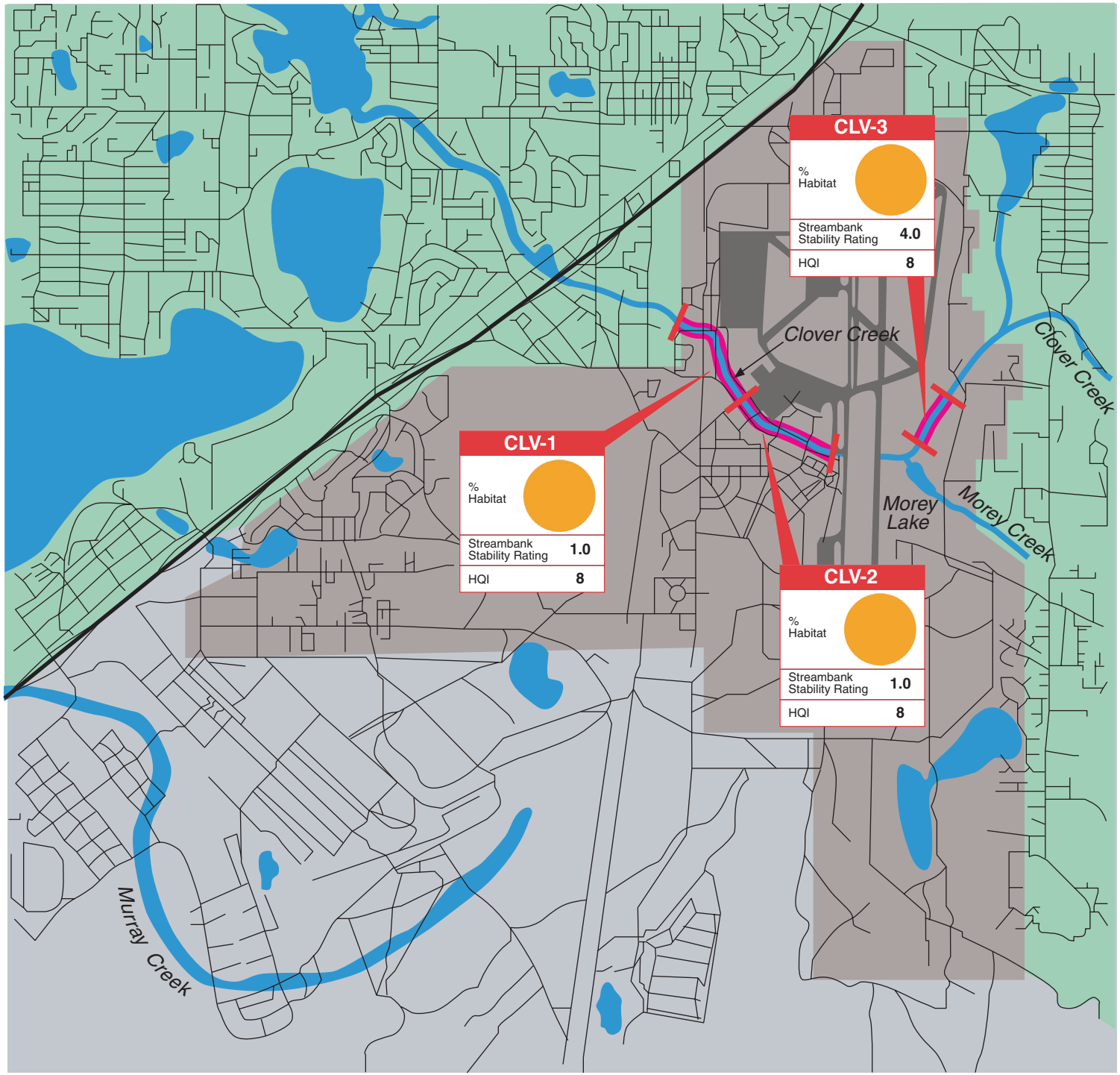
McChord Air Force Base Clover Creek Instream Habitat Assessment Map



LEGEND

- McChord AFB
- Flight Operations Area (Runway)
- Ft. Lewis Army Base
- Off Base
- Streams, lakes and wetlands
- Roads
- Survey reach location (CLV-1)
- *See Map Legend F-9 for explanation*

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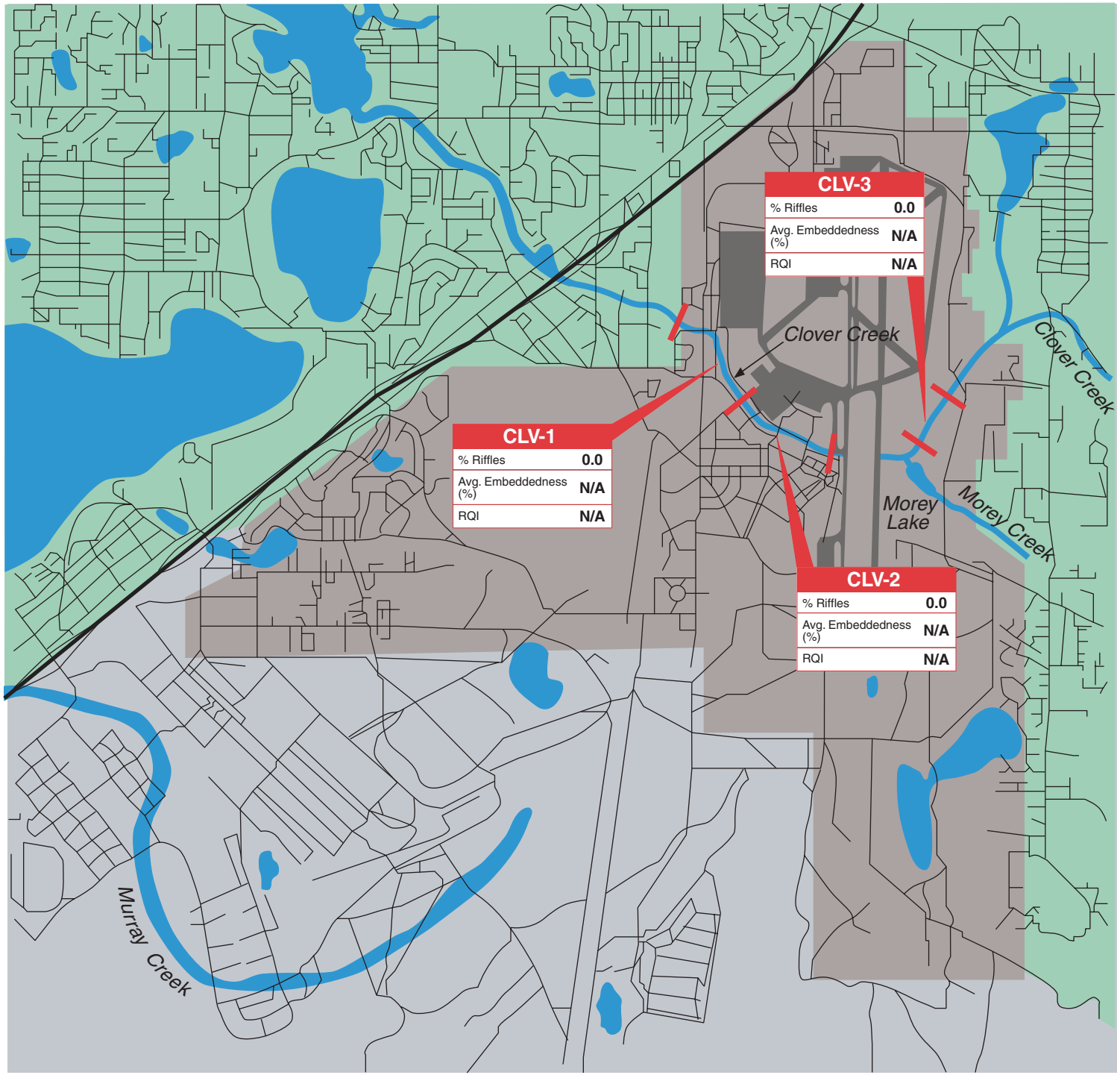
McChord Air Force Base Clover Creek Spawning Habitat Assessment Map



LEGEND

- McChord AFB
- Flight Operations Area (Runway)
- Ft. Lewis Army Base
- Off Base
- Streams, lakes and wetlands
- Roads
- CLV-1 Survey reach location
- CLV-3 *See Map Legend F-9 for explanation*

N W E S

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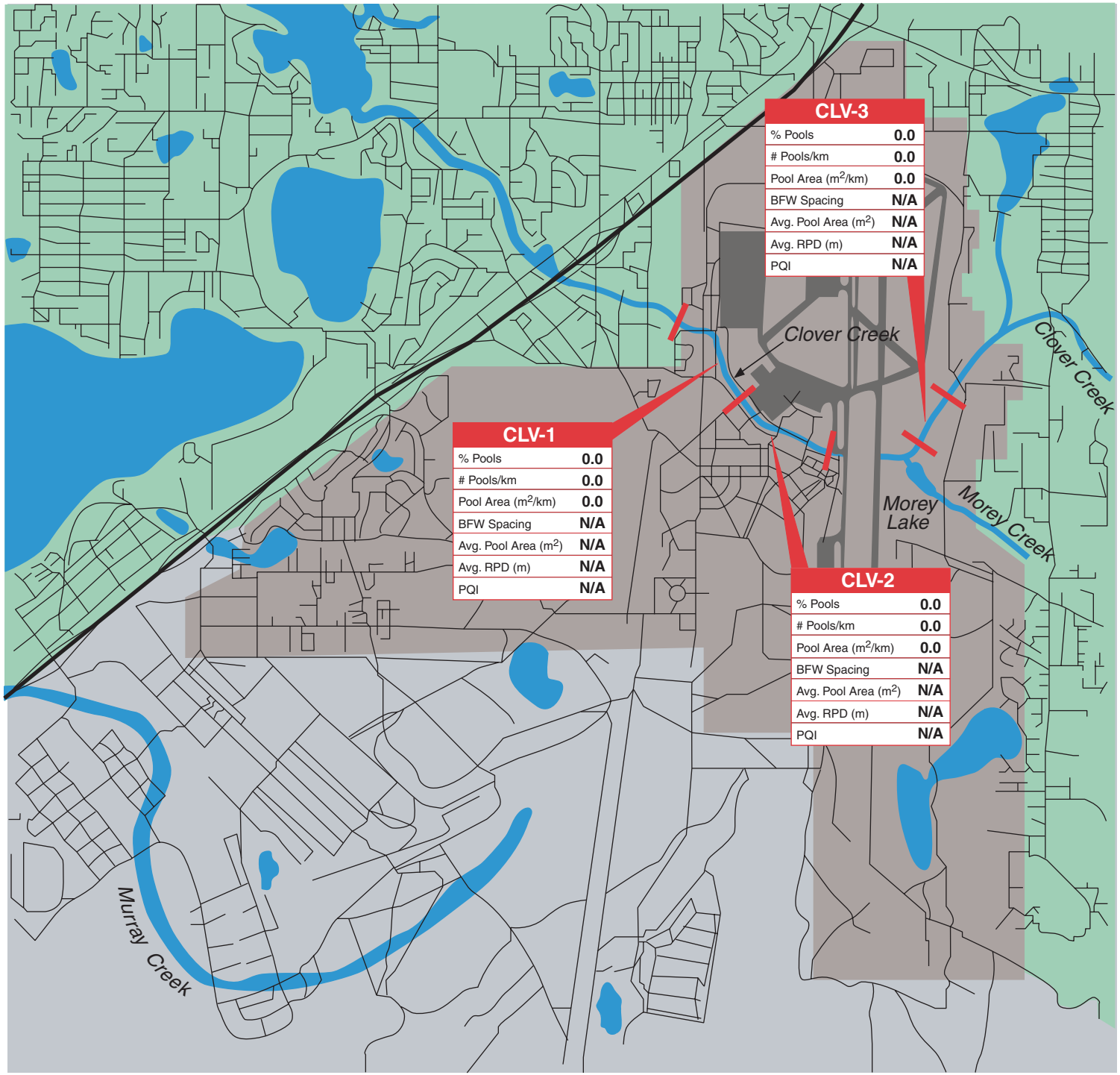
McChord Air Force Base Clover Creek Rearing Habitat Assessment Map



LEGEND

- McChord AFB
- Flight Operations Area (Runway)
- Ft. Lewis Army Base
- Off Base
- Streams, lakes and wetlands
- Roads
- CLV-1 Survey reach location

CLV-3
% Pools 0.0
# Pools/km 0.0
Pool Area (m2/km) 0.0
BFW Spacing N/A
Avg. Pool Area (m2) N/A
Avg. RPD (m) N/A
PQI N/A

See Map Legend F-9 for explanation

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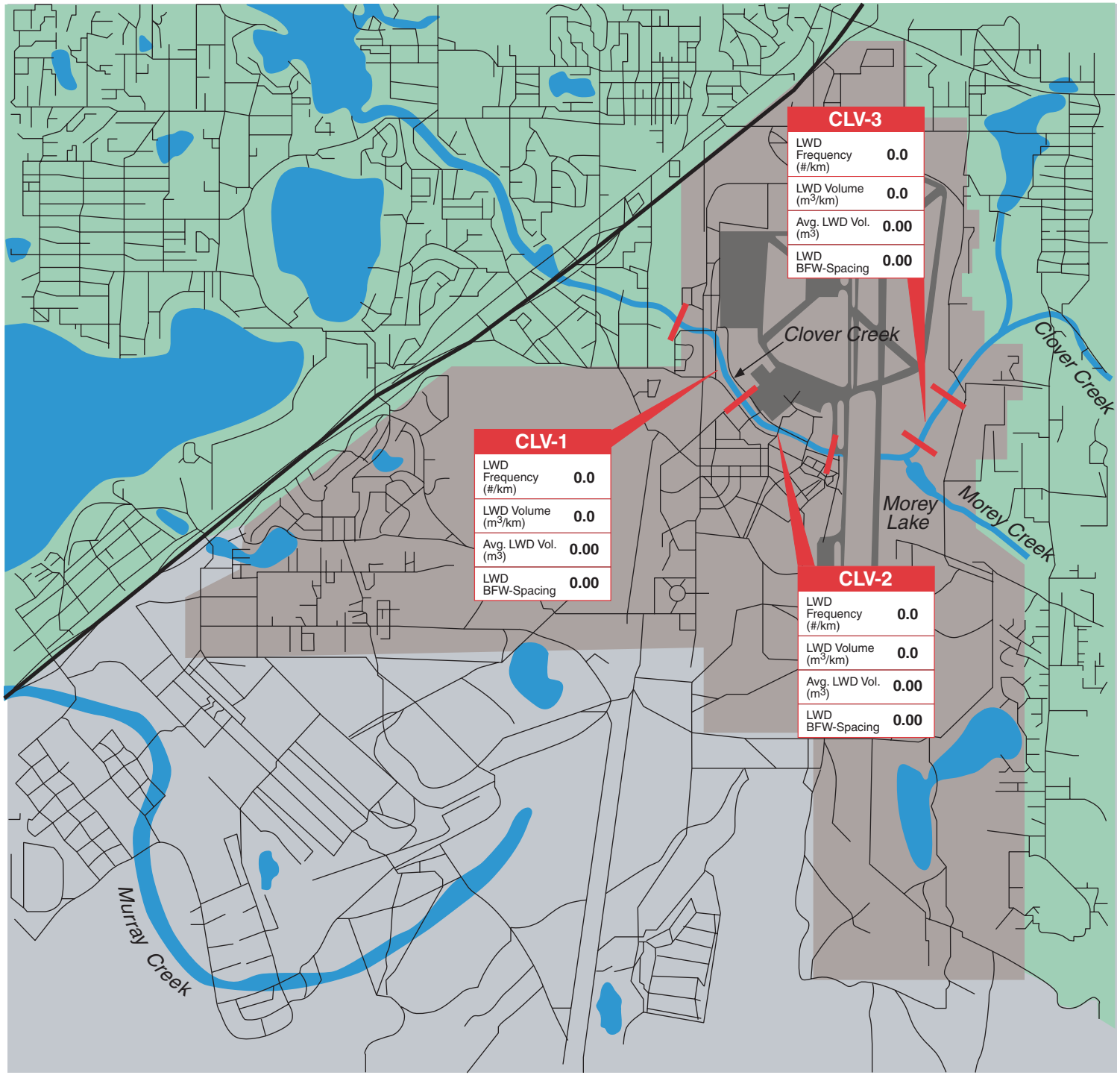
miles

McChord Air Force Base Clover Creek Large Woody Debris (LWD) Survey Map



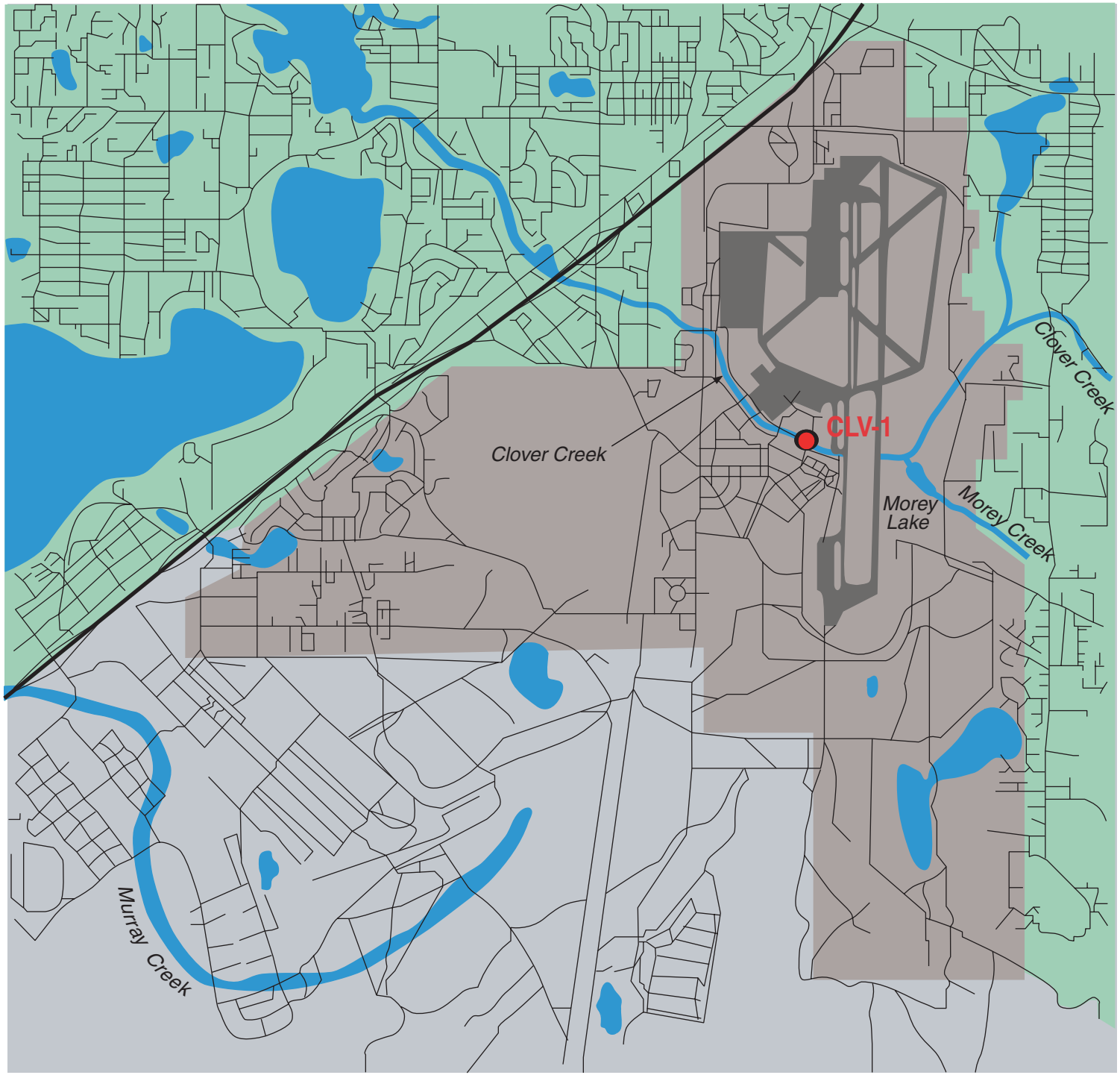
LEGEND

- McChord AFB
- Flight Operations Area (Runway)
- Ft. Lewis Army Base
- Off Base
- Streams, lakes and wetlands
- Roads
- CLV-1 Survey reach location
- CLV-3 *See Map Legend F-9 for explanation*

N W E S

0 0.5 1 miles

McChord Air Force Base Clover Creek Biological Monitoring Site Map



LEGEND

- McChord AFB
- Flight Operations Area (Runway)
- Ft. Lewis Army Base
- Off Base
- Streams, lakes and wetlands
- Roads
- Bio-monitoring site

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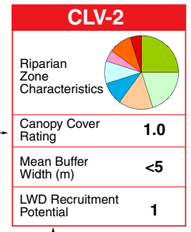
miles

RIPARIAN CONDITIONS LEGEND



Survey Reach Identification

Relative Percentages of Riparian Zone Characteristics:

- Mature Coniferous
- Young Coniferous
- Mature Deciduous
- Young Deciduous
- Mixed Mature
- Mixed Young
- Prairie
- Woody Shrubs
- Herbaceous Tall
- Herbaceous Short
- Landscaped
- Lawn/Turf
- Impervious

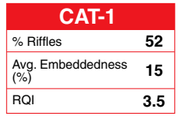
Canopy Cover Rating

80-100% Canopy Cover = 4
60-80% Canopy Cover = 3
40-60% Canopy Cover = 2
0-40% Canopy Cover = 1

LWD Recruitment Potential

Mature Coniferous Riparian w/adequate LWD = 4
Mixed Mature Riparian or w/o adequate LWD = 3
Mature Deciduous Riparian and/or w/o adequate LWD = 2
Lack of Riparian Forest & w/o adequate LWD = 1

SPAWNING HABITAT LEGEND



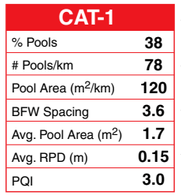
Survey Reach Identification

% Total Instream Habitat (Surface Area) in Riffles (40-60% is optimum)

Average Substrata Embeddedness (<10% is optimum)

Riffle Quality Index = Qualitative Rating of Spawning Habitat Quality (5 = excellent quality and 1 = poor quality)

REARING HABITAT LEGEND



Survey Reach Identification

% Total Instream Habitat (Surface Area) in Pools (40-60% is optimum)

Pool Frequency per km of Stream

Pool Area per km of Stream

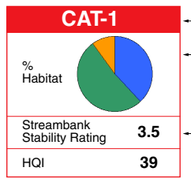
Bankfull-Width Spacings Between Pools (≤2 is optimum)

Average Area of Pools within Survey Reach

Average Residual Pool Depth

Pool Quality Index = A Qualitative Rating of Rearing Habitat Quality (5 = excellent quality and 1 = poor quality)

INSTREAM HABITAT CONDITIONS LEGEND



Survey Reach Identification

Relative Percentages of Instream Habitat Characteristics: % Pool % Riffle % Glide

Streambank Stability Rating

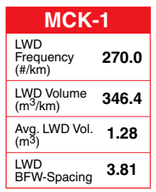
75-100% Stable/Vegetated = 4
50-75% Stable/Vegetated = 3
25-50% Stable/Vegetated = 2
0-25% Stable/Vegetated = 1

HQI Score

>40	Excellent	
30-40	Good	
20-30	Fair	
<20	Poor	

Shown along respective surveyed reach

LARGE WOODY DEBRIS (LWD) LEGEND



Survey Reach Identification

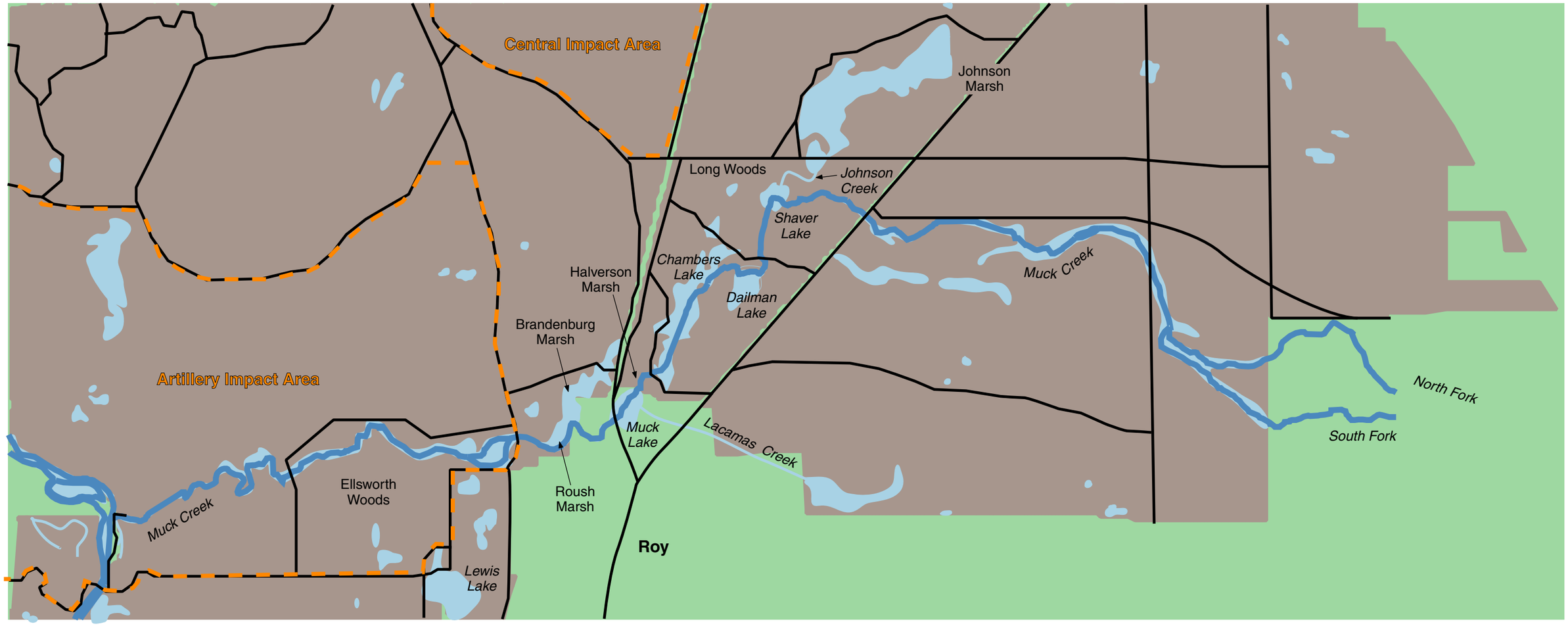
Frequency of LWD within Survey Reach

Volume of LWD within Survey Reach

Average Volume (size) of LWD within Survey Reach

Pieces of LWD per Bankfull-Width Spacing (≥2 is optimum)

Fort Lewis
Muck Creek
Base Map



LEGEND

- Ft. Lewis Army Base
- Off Base
- Impact Area Boundary
- Lakes and wetlands
- Streams and creeks
- Roads

N W E S

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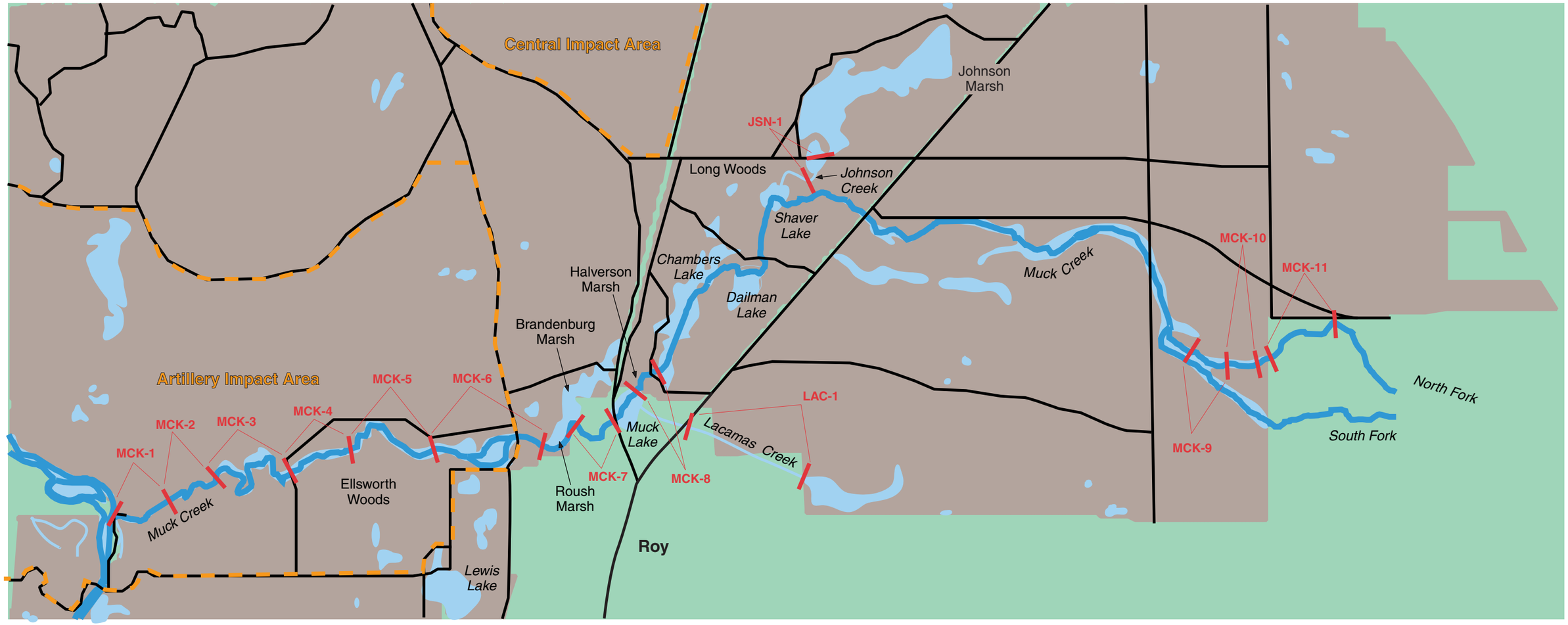
miles

Fort Lewis
Muck Creek
Stream Survey Reach Map



LEGEND

- Ft. Lewis Army Base
- Off Base
- Impact Area Boundary
- Lakes and wetlands
- Streams and creeks
- Roads
- Survey reach location (MCK-1)

N W E S

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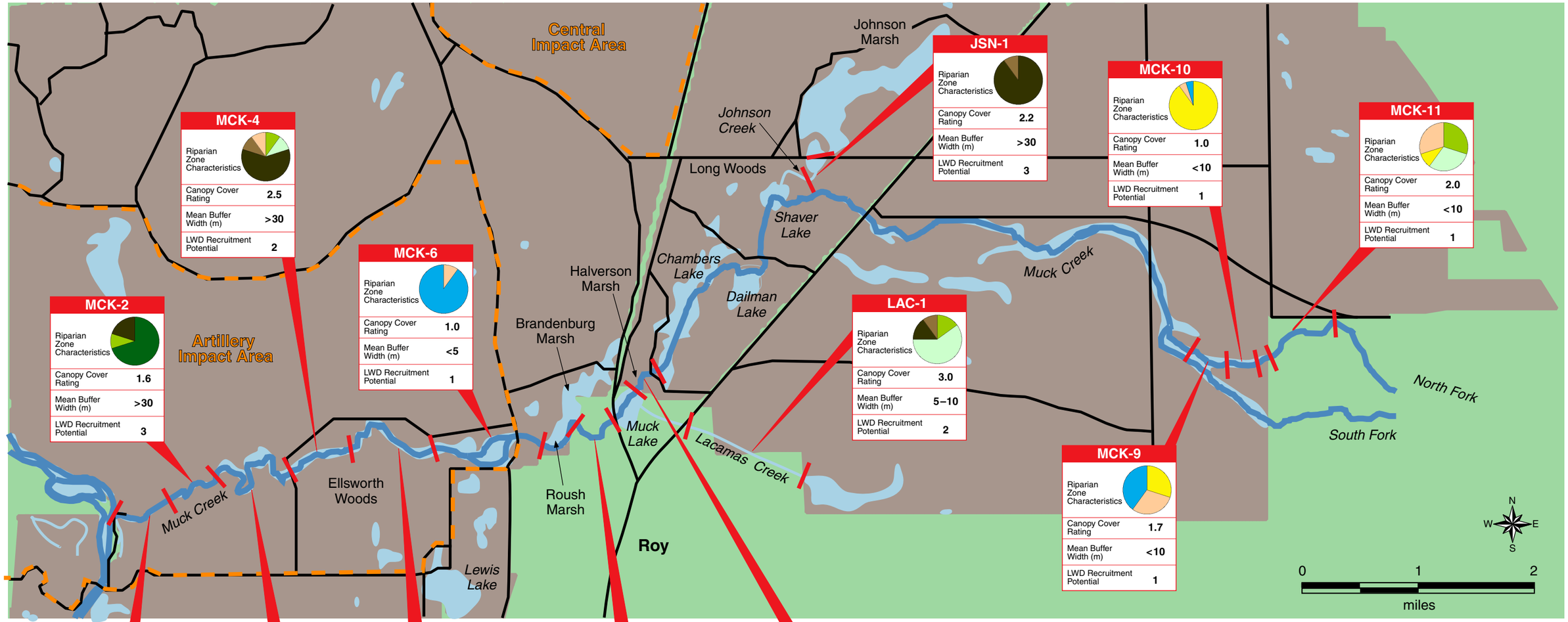
miles

Fort Lewis
Muck Creek
Riparian Conditions Map



MCK-1

Riparian Zone Characteristics	
Canopy Cover Rating	1.7
Mean Buffer Width (m)	>30
LWD Recruitment Potential	3

MCK-2

Riparian Zone Characteristics	
Canopy Cover Rating	1.6
Mean Buffer Width (m)	>30
LWD Recruitment Potential	3

MCK-3

Riparian Zone Characteristics	
Canopy Cover Rating	2.2
Mean Buffer Width (m)	>30
LWD Recruitment Potential	2

MCK-4

Riparian Zone Characteristics	
Canopy Cover Rating	2.5
Mean Buffer Width (m)	>30
LWD Recruitment Potential	2

MCK-5

Riparian Zone Characteristics	
Canopy Cover Rating	1.6
Mean Buffer Width (m)	5–10
LWD Recruitment Potential	2

MCK-6

Riparian Zone Characteristics	
Canopy Cover Rating	1.0
Mean Buffer Width (m)	<5
LWD Recruitment Potential	1

MCK-7

Riparian Zone Characteristics	
Canopy Cover Rating	1.8
Mean Buffer Width (m)	5–10
LWD Recruitment Potential	1

MCK-8

Riparian Zone Characteristics	
Canopy Cover Rating	2.8
Mean Buffer Width (m)	5–10
LWD Recruitment Potential	3

MCK-9

Riparian Zone Characteristics	
Canopy Cover Rating	1.7
Mean Buffer Width (m)	<10
LWD Recruitment Potential	1

MCK-10

Riparian Zone Characteristics	
Canopy Cover Rating	1.0
Mean Buffer Width (m)	<10
LWD Recruitment Potential	1

MCK-11

Riparian Zone Characteristics	
Canopy Cover Rating	2.0
Mean Buffer Width (m)	<10
LWD Recruitment Potential	1

JSN-1

Riparian Zone Characteristics	
Canopy Cover Rating	2.2
Mean Buffer Width (m)	>30
LWD Recruitment Potential	3

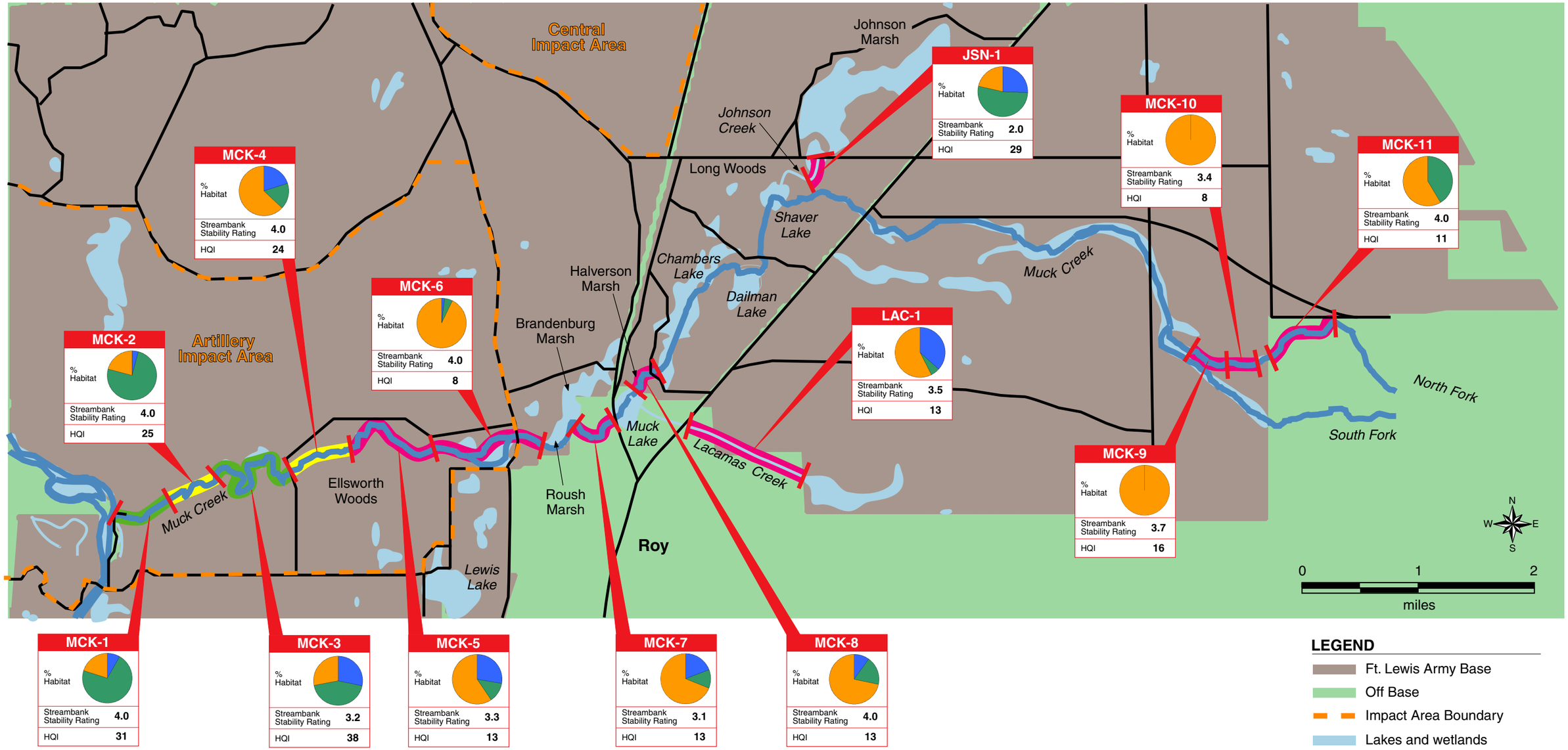
LAC-1

Riparian Zone Characteristics	
Canopy Cover Rating	3.0
Mean Buffer Width (m)	5–10
LWD Recruitment Potential	2

LEGEND

- Ft. Lewis Army Base
- Off Base
- Impact Area Boundary
- Lakes and wetlands
- Streams and creeks
- Roads
- Survey reach location (MCK-1)
- *See Map Legend G-9 for explanation*

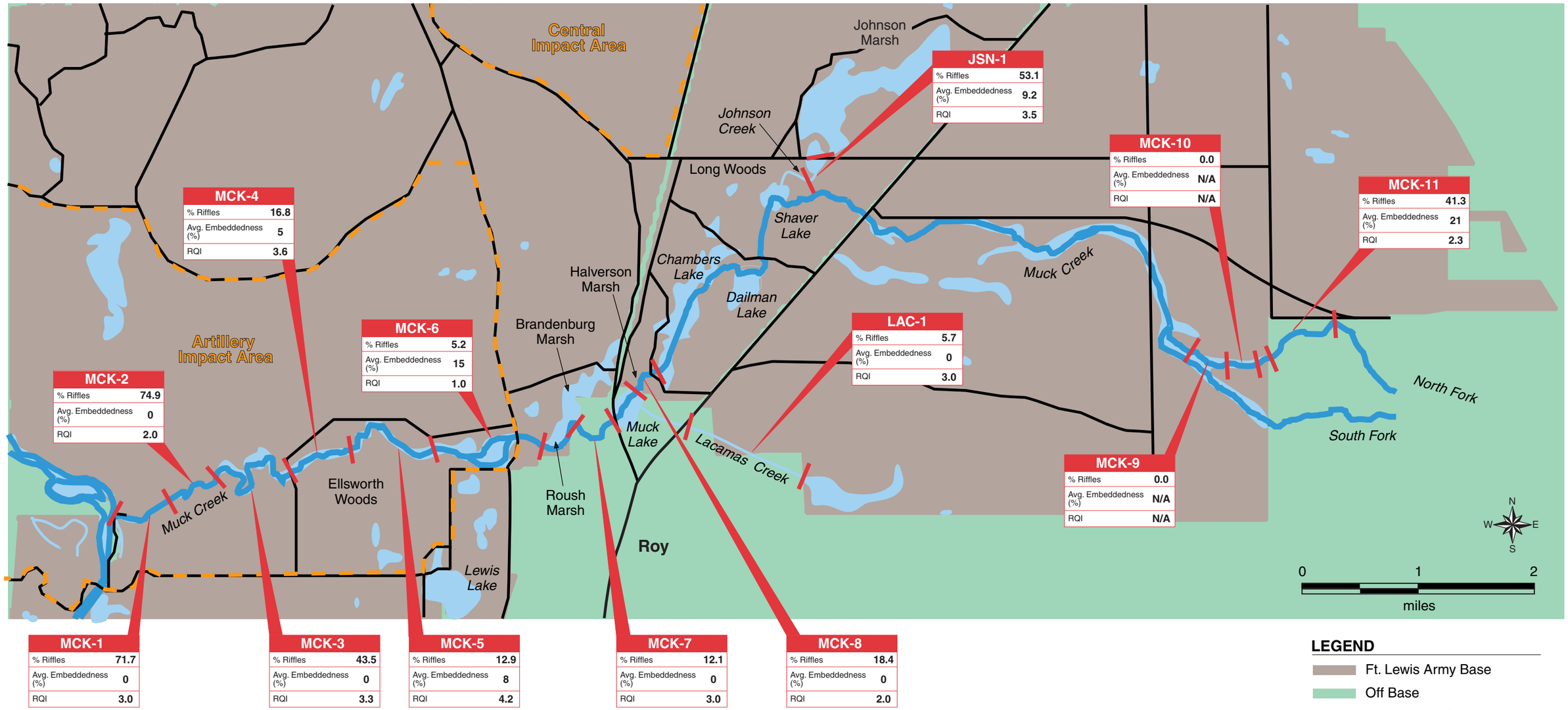
Fort Lewis
Muck Creek
Instream Habitat Assessment Map



LEGEND

- Ft. Lewis Army Base
- Off Base
- Impact Area Boundary
- Lakes and wetlands
- Streams and creeks
- Roads
- Survey reach location (MCK-1)
- *See Map Legend G-9 for explanation*

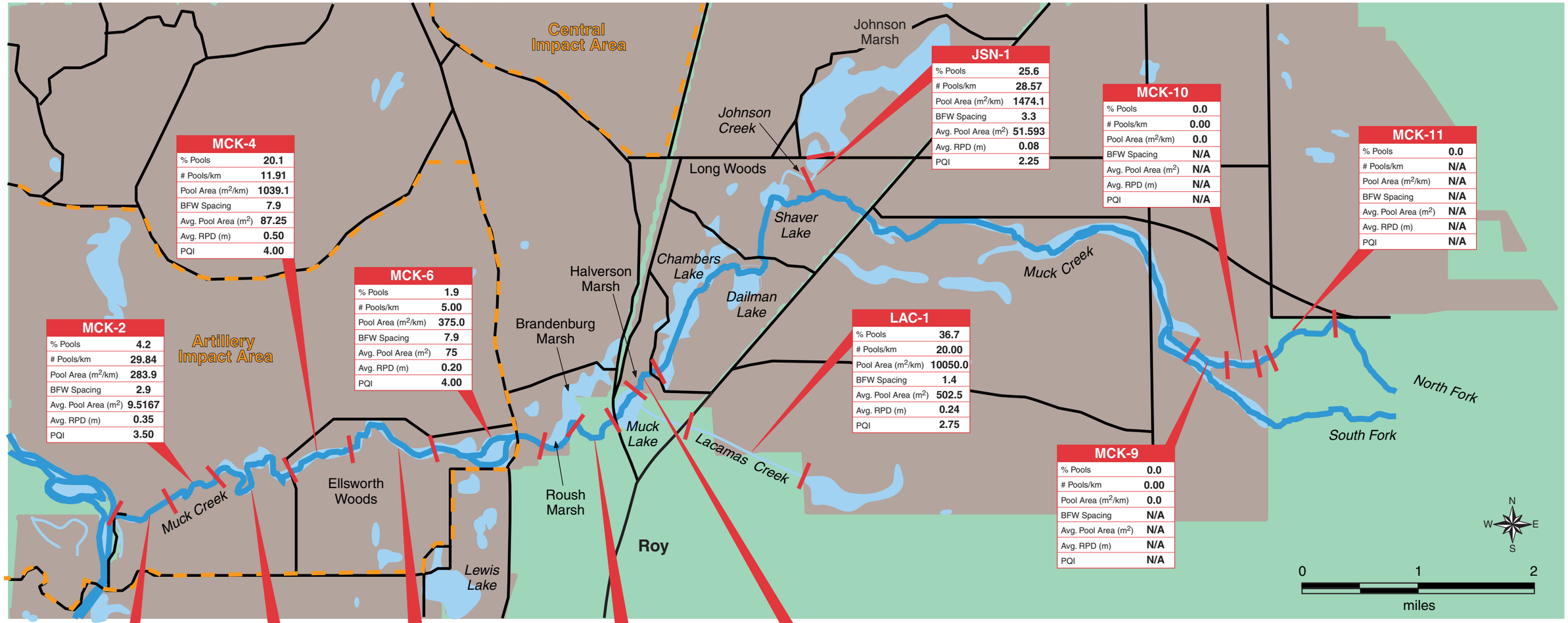
Fort Lewis
Muck Creek
Spawning Habitat Assessment Map



LEGEND

- Ft. Lewis Army Base
- Off Base
- Impact Area Boundary
- Lakes and wetlands
- Streams and creeks
- Roads
- Survey reach location (MCK-1)
- *See Map Legend G-9 for explanation*

Fort Lewis
Muck Creek
Rearing Habitat Assessment Map



MCK-1	
% Pools	8.2
# Pools/km	23.33
Pool Area (m^2/km)	520.7
BFW Spacing	3.0
Avg. Pool Area (m^2)	22.314
Avg. RPD (m)	0.48
PQI	3.71

MCK-2	
% Pools	4.2
# Pools/km	29.84
Pool Area (m^2/km)	283.9
BFW Spacing	2.9
Avg. Pool Area (m^2)	9.5167
Avg. RPD (m)	0.35
PQI	3.50

MCK-3	
% Pools	28.4
# Pools/km	58.54
Pool Area (m^2/km)	1663.7
BFW Spacing	1.2
Avg. Pool Area (m^2)	28.421
Avg. RPD (m)	0.22
PQI	3.44

MCK-4	
% Pools	20.1
# Pools/km	11.91
Pool Area (m^2/km)	1039.1
BFW Spacing	7.9
Avg. Pool Area (m^2)	87.25
Avg. RPD (m)	0.50
PQI	4.00

MCK-5	
% Pools	27.8
# Pools/km	22.54
Pool Area (m^2/km)	1641.9
BFW Spacing	4.0
Avg. Pool Area (m^2)	72.844
Avg. RPD (m)	0.59
PQI	4.00

MCK-6	
% Pools	1.9
# Pools/km	5.00
Pool Area (m^2/km)	375.0
BFW Spacing	7.9
Avg. Pool Area (m^2)	75
Avg. RPD (m)	0.20
PQI	4.00

MCK-7	
% Pools	19.0
# Pools/km	17.99
Pool Area (m^2/km)	1238.4
BFW Spacing	5.5
Avg. Pool Area (m^2)	68.853
Avg. RPD (m)	0.18
PQI	2.57

MCK-8	
% Pools	10.0
# Pools/km	14.55
Pool Area (m^2/km)	511.5
BFW Spacing	6.6
Avg. Pool Area (m^2)	35.16
Avg. RPD (m)	0.30
PQI	2.00

LAC-1	
% Pools	36.7
# Pools/km	20.00
Pool Area (m^2/km)	10050.0
BFW Spacing	1.4
Avg. Pool Area (m^2)	502.5
Avg. RPD (m)	0.24
PQI	2.75

JSN-1	
% Pools	25.6
# Pools/km	28.57
Pool Area (m^2/km)	1474.1
BFW Spacing	3.3
Avg. Pool Area (m^2)	51.593
Avg. RPD (m)	0.08
PQI	2.25

MCK-9	
% Pools	0.0
# Pools/km	0.00
Pool Area (m^2/km)	0.0
BFW Spacing	N/A
Avg. Pool Area (m^2)	N/A
Avg. RPD (m)	N/A
PQI	N/A

MCK-10	
% Pools	0.0
# Pools/km	0.00
Pool Area (m^2/km)	0.0
BFW Spacing	N/A
Avg. Pool Area (m^2)	N/A
Avg. RPD (m)	N/A
PQI	N/A

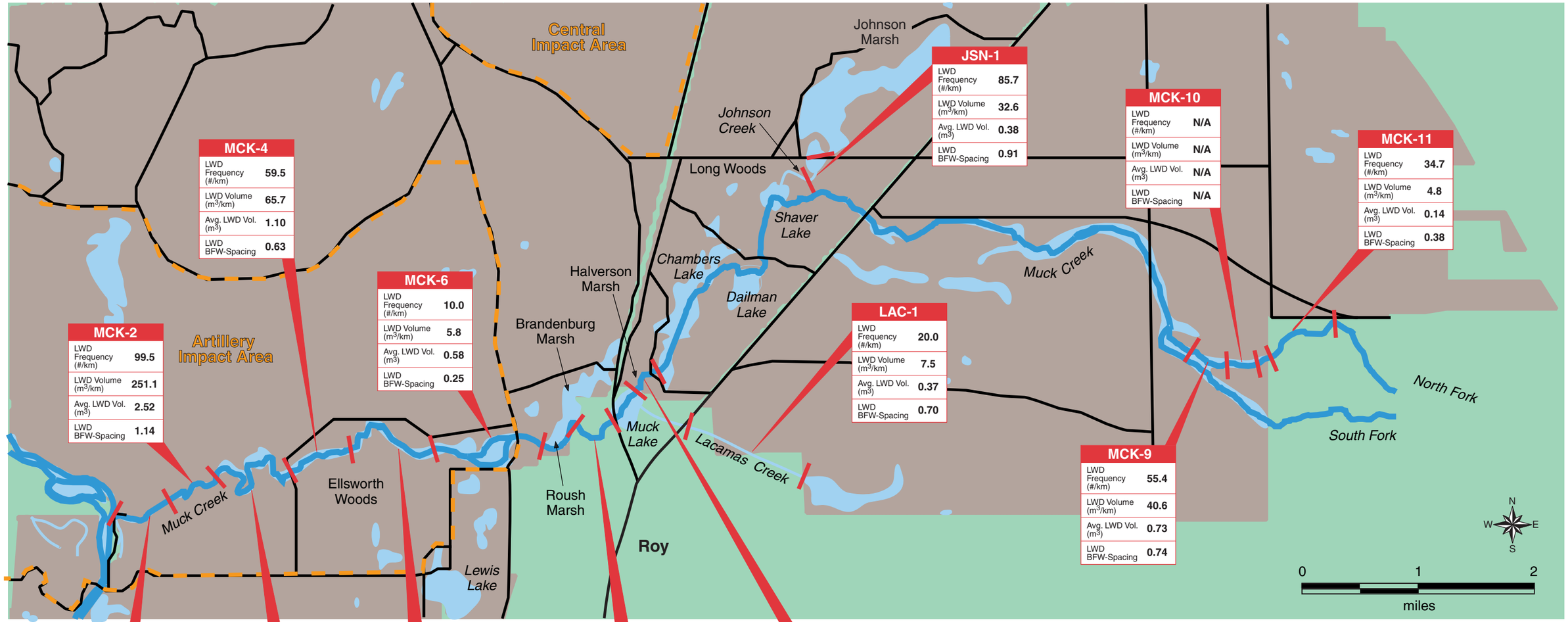
MCK-11	
% Pools	0.0
# Pools/km	N/A
Pool Area (m^2/km)	N/A
BFW Spacing	N/A
Avg. Pool Area (m^2)	N/A
Avg. RPD (m)	N/A
PQI	N/A

LEGEND

- Ft. Lewis Army Base
- Off Base
- Impact Area Boundary
- Lakes and wetlands
- Streams and creeks
- Roads
- Survey reach location (MCK-1)

See Map Legend G-9 for explanation

Fort Lewis
Muck Creek
Large Woody Debris (LWD) Survey Map



JSN-1	
LWD Frequency (#/km)	85.7
LWD Volume (m^3/km)	32.6
Avg. LWD Vol. (m^3)	0.38
LWD BFW-Spacing	0.91

MCK-10	
LWD Frequency (#/km)	N/A
LWD Volume (m^3/km)	N/A
Avg. LWD Vol. (m^3)	N/A
LWD BFW-Spacing	N/A

MCK-11	
LWD Frequency (#/km)	34.7
LWD Volume (m^3/km)	4.8
Avg. LWD Vol. (m^3)	0.14
LWD BFW-Spacing	0.38

MCK-4	
LWD Frequency (#/km)	59.5
LWD Volume (m^3/km)	65.7
Avg. LWD Vol. (m^3)	1.10
LWD BFW-Spacing	0.63

MCK-6	
LWD Frequency (#/km)	10.0
LWD Volume (m^3/km)	5.8
Avg. LWD Vol. (m^3)	0.58
LWD BFW-Spacing	0.25

LAC-1	
LWD Frequency (#/km)	20.0
LWD Volume (m^3/km)	7.5
Avg. LWD Vol. (m^3)	0.37
LWD BFW-Spacing	0.70

MCK-2	
LWD Frequency (#/km)	99.5
LWD Volume (m^3/km)	251.1
Avg. LWD Vol. (m^3)	2.52
LWD BFW-Spacing	1.14

MCK-9	
LWD Frequency (#/km)	55.4
LWD Volume (m^3/km)	40.6
Avg. LWD Vol. (m^3)	0.73
LWD BFW-Spacing	0.74

MCK-1	
LWD Frequency (#/km)	270.0
LWD Volume (m^3/km)	346.4
Avg. LWD Vol. (m^3)	1.28
LWD BFW-Spacing	3.81

MCK-3	
LWD Frequency (#/km)	258.5
LWD Volume (m^3/km)	281.2
Avg. LWD Vol. (m^3)	1.09
LWD BFW-Spacing	3.83

MCK-5	
LWD Frequency (#/km)	42.6
LWD Volume (m^3/km)	25.2
Avg. LWD Vol. (m^3)	0.59
LWD BFW-Spacing	0.47

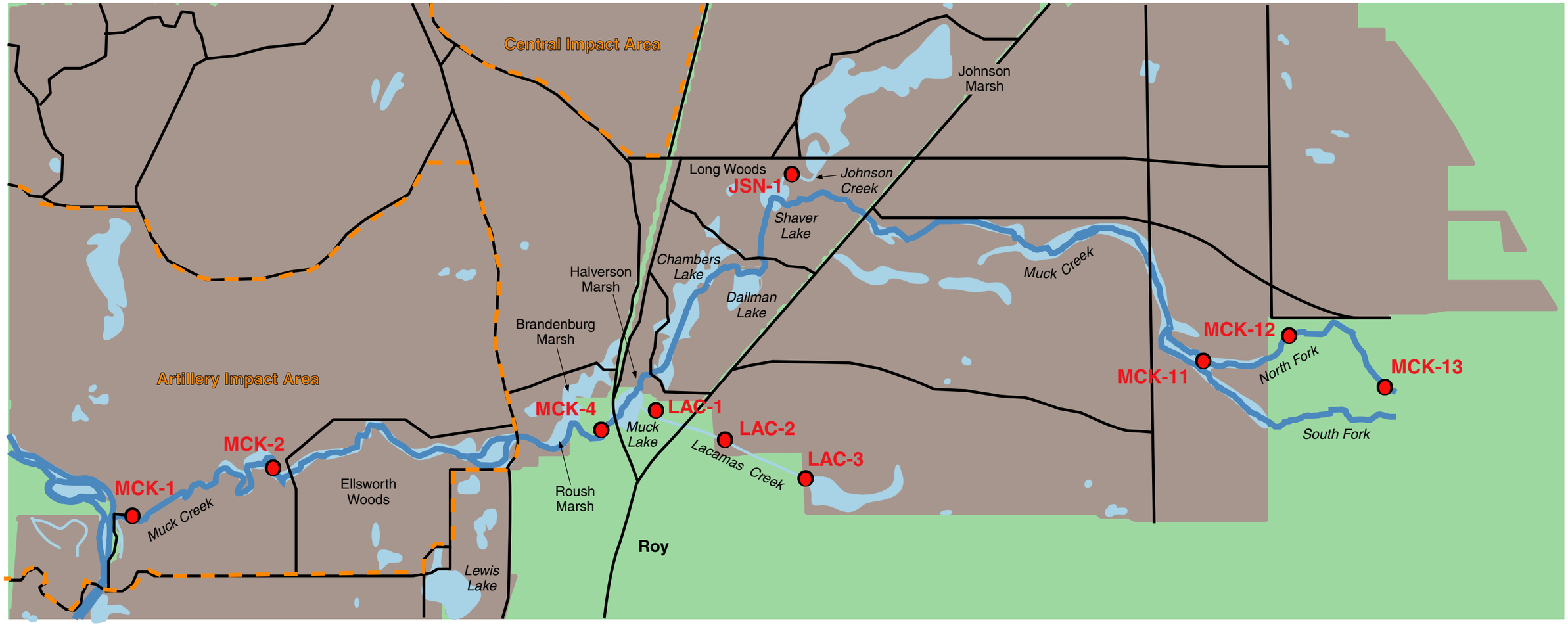
MCK-7	
LWD Frequency (#/km)	22.0
LWD Volume (m^3/km)	6.5
Avg. LWD Vol. (m^3)	0.29
LWD BFW-Spacing	0.22

MCK-8	
LWD Frequency (#/km)	26.2
LWD Volume (m^3/km)	17.4
Avg. LWD Vol. (m^3)	0.66
LWD BFW-Spacing	0.27

LEGEND

- Ft. Lewis Army Base
- Off Base
- Impact Area Boundary
- Lakes and wetlands
- Streams and creeks
- Roads
- Survey reach location (MCK-1)
- *See Map Legend G-9 for explanation*

Fort Lewis
Muck Creek
Biological Monitoring Site Map



LEGEND

- Ft. Lewis Army Base
- Off Base
- Impact Area Boundary
- Lakes and wetlands
- Streams and creeks
- Roads
- Bio-monitoring site

N W E S

0 1 2
miles

RIPARIAN CONDITIONS LEGEND

CLV-2	
Riparian Zone Characteristics	
Canopy Cover Rating	1.0
Mean Buffer Width (m)	<5
LWD Recruitment Potential	1

Survey Reach Identification

Relative Percentages of Riparian Zone Characteristics:

- Mature Coniferous
- Young Coniferous
- Mature Deciduous
- Young Deciduous
- Mixed Mature
- Mixed Young
- Prairie
- Woody Shrubs
- Herbaceous Tall
- Herbaceous Short
- Landscaped
- Lawn/Turf
- Impervious

Canopy Cover Rating

80-100% Canopy Cover = 4
60-80% Canopy Cover = 3
40-60% Canopy Cover = 2
0-40% Canopy Cover = 1

LWD Recruitment Potential

Mature Coniferous Riparian w/adequate LWD = 4
Mixed Mature Riparian or w/o adequate LWD = 3
Mature Deciduous Riparian and/or w/o adequate LWD = 2
Lack of Riparian Forest & w/o adequate LWD = 1

SPAWNING HABITAT LEGEND

CAT-1	
% Riffles	52
Avg. Embeddedness (%)	15
RQI	3.5

% Total Instream Habitat (Surface Area) in Riffles (40-60% is optimum)

Riffle Quality Index = Qualitative Rating of Spawning Habitat Quality (5 = excellent quality and 1 = poor quality)

Survey Reach Identification

Average Substrata Embeddedness (<10% is optimum)

REARING HABITAT LEGEND

CAT-1	
% Pools	38
# Pools/km	78
Pool Area (m^2/km)	120
BFW Spacing	3.6
Avg. Pool Area (m^2)	1.7
Avg. RPD (m)	0.15
PQI	3.0

% Total Instream Habitat (Surface Area) in Pools (40-60% is optimum)

Pool Area per km of Stream

Average Area of Pools within Survey Reach

Pool Quality Index = A Qualitative Rating of Rearing Habitat Quality (5 = excellent quality and 1 = poor quality)

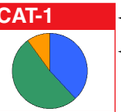
Survey Reach Identification

Pool Frequency per km of Stream

Bankfull-Width Spacings Between Pools (≤2 is optimum)

Average Residual Pool Depth

INSTREAM HABITAT CONDITIONS LEGEND

CAT-1	
% Habitat	
Streambank Stability Rating	3.5
HQI	39

Survey Reach Identification

Relative Percentages of Instream Habitat Characteristics: % Pool % Riffle % Glide

Streambank Stability Rating

75-100% Stable/Vegetated = 4
50-75% Stable/Vegetated = 3
25-50% Stable/Vegetated = 2
0-25% Stable/Vegetated = 1

HQI Score

>40	Excellent	
30-40	Good	
20-30	Fair	
<20	Poor	

Shown along respective surveyed reach

LARGE WOODY DEBRIS (LWD) LEGEND

MCK-1	
LWD Frequency (#/km)	270.0
LWD Volume (m^3/km)	346.4
Avg. LWD Vol. (m^3)	1.28
LWD BFW-Spacing	3.81

Survey Reach Identification

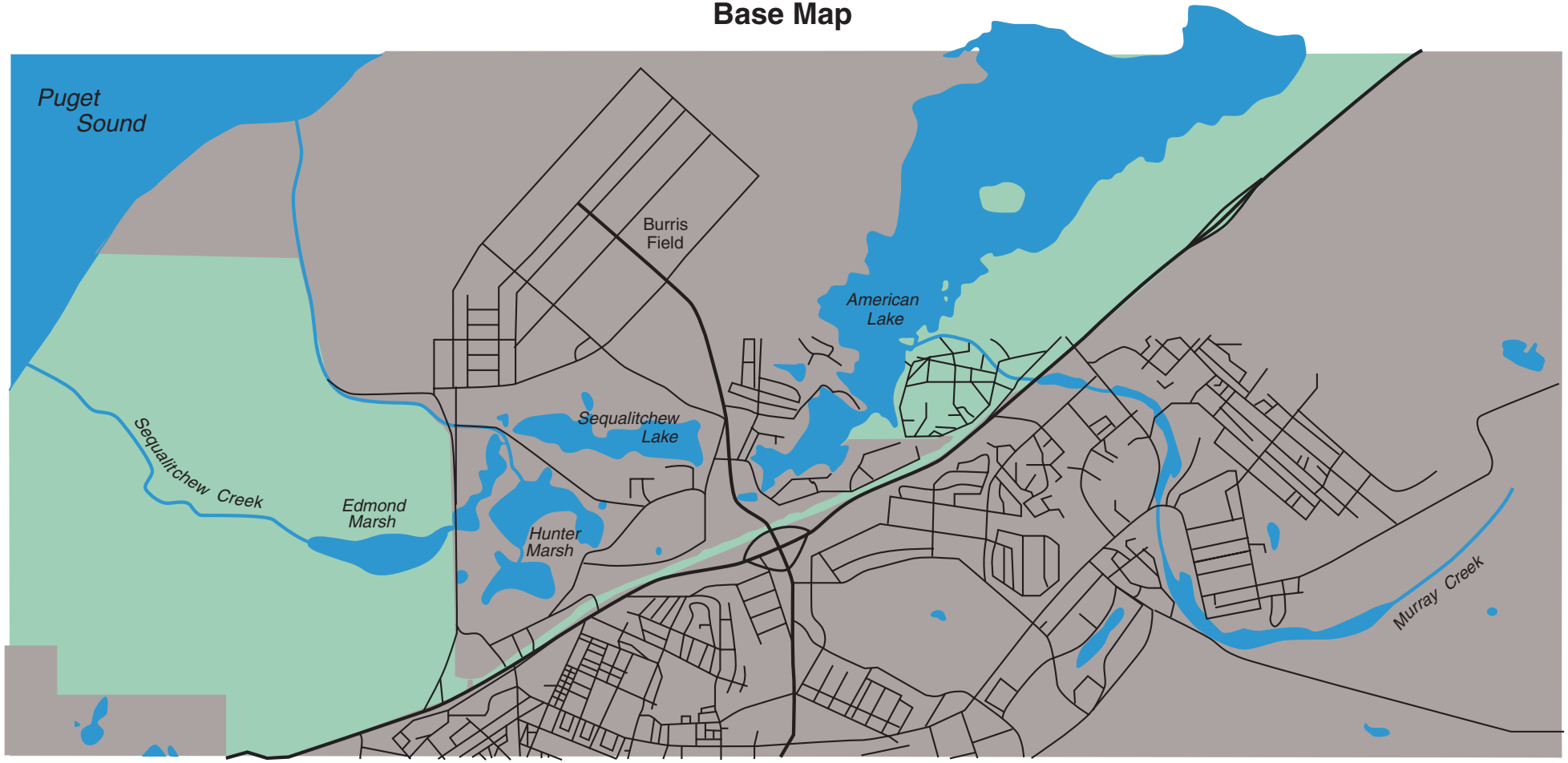
Frequency of LWD within Survey Reach

Volume of LWD within Survey Reach

Average Volume (size) of LWD within Survey Reach

Pieces of LWD per Bankfull-Width Spacing (≥2 is optimum)

Fort Lewis
Sequalitchew and Murray Creeks
Base Map



LEGEND

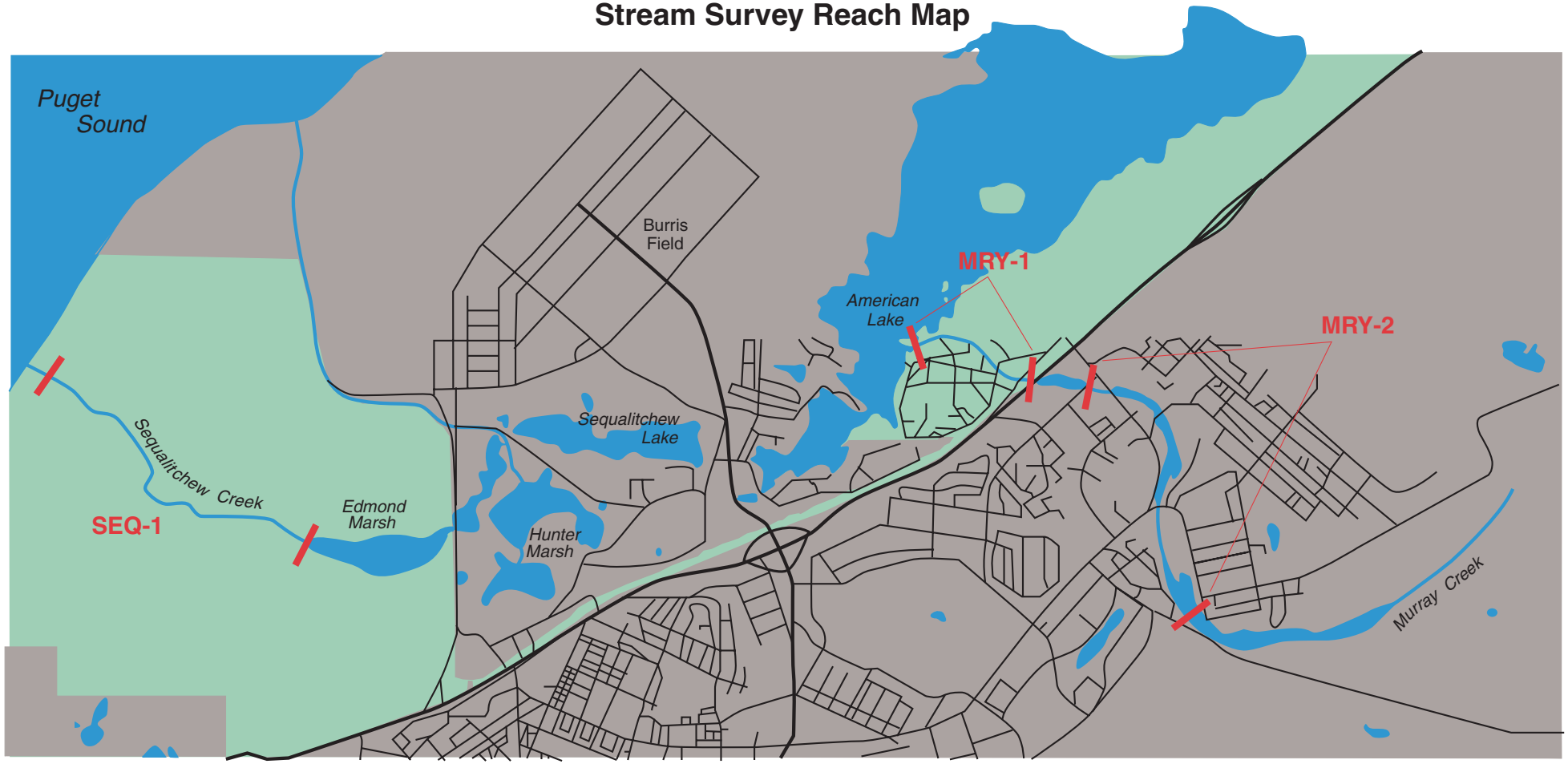
- Base
- Off Base
- Streams, lakes and wetlands
- Roads

N
W E
S

0 0.5 1
miles

Map H-1

Fort Lewis
Sequalitchew and Murray Creeks
Stream Survey Reach Map



LEGEND

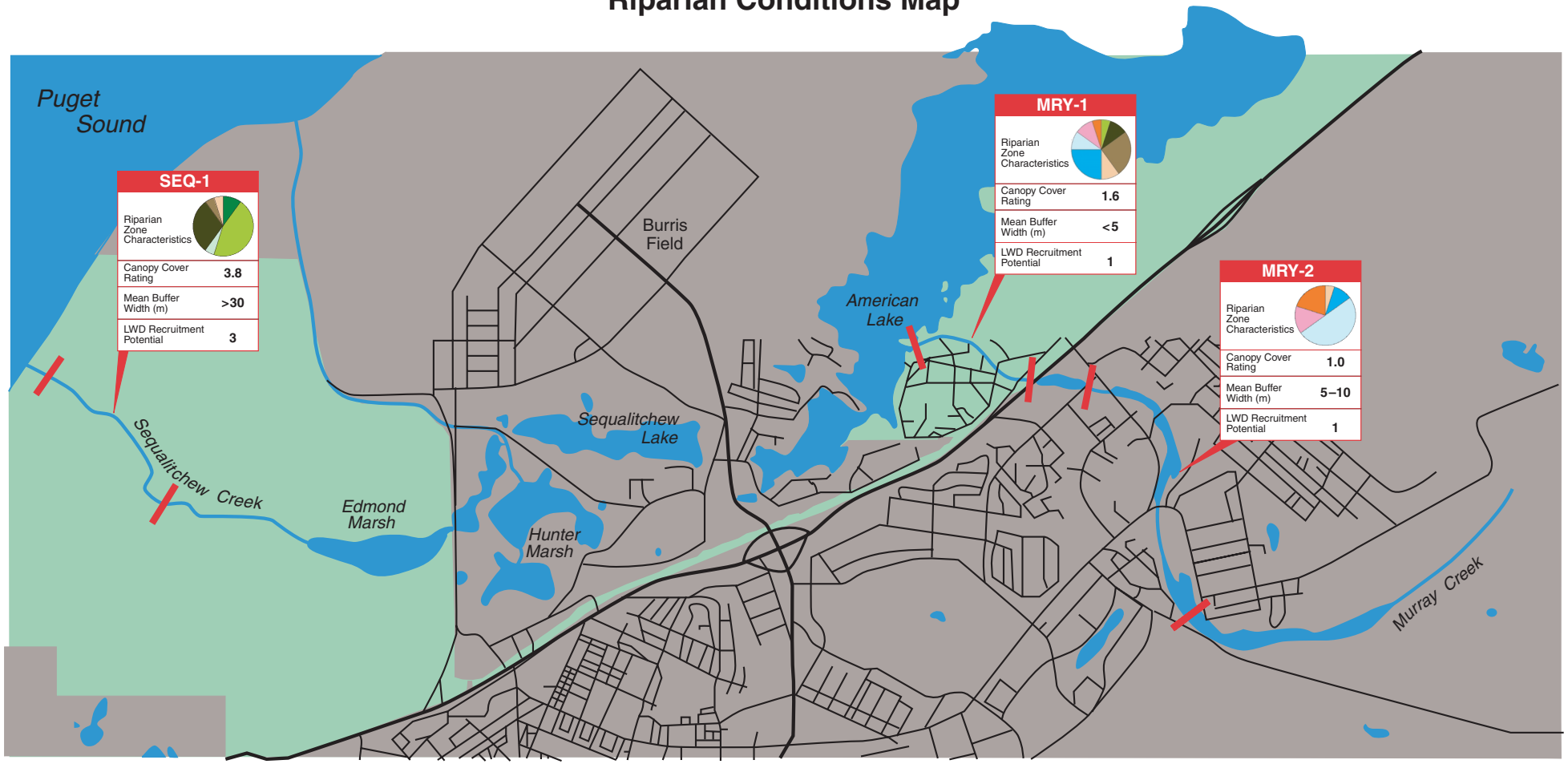
- Base
- Off Base
- Streams, lakes and wetlands
- Roads
- Survey reach location (SEQ-1)

N W E S

0 0.5 1
miles

Map H-2

Fort Lewis
Sequalitchew and Murray Creeks
Riparian Conditions Map



LEGEND

- Base
- Off Base
- Streams, lakes and wetlands
- Roads
- Survey reach location

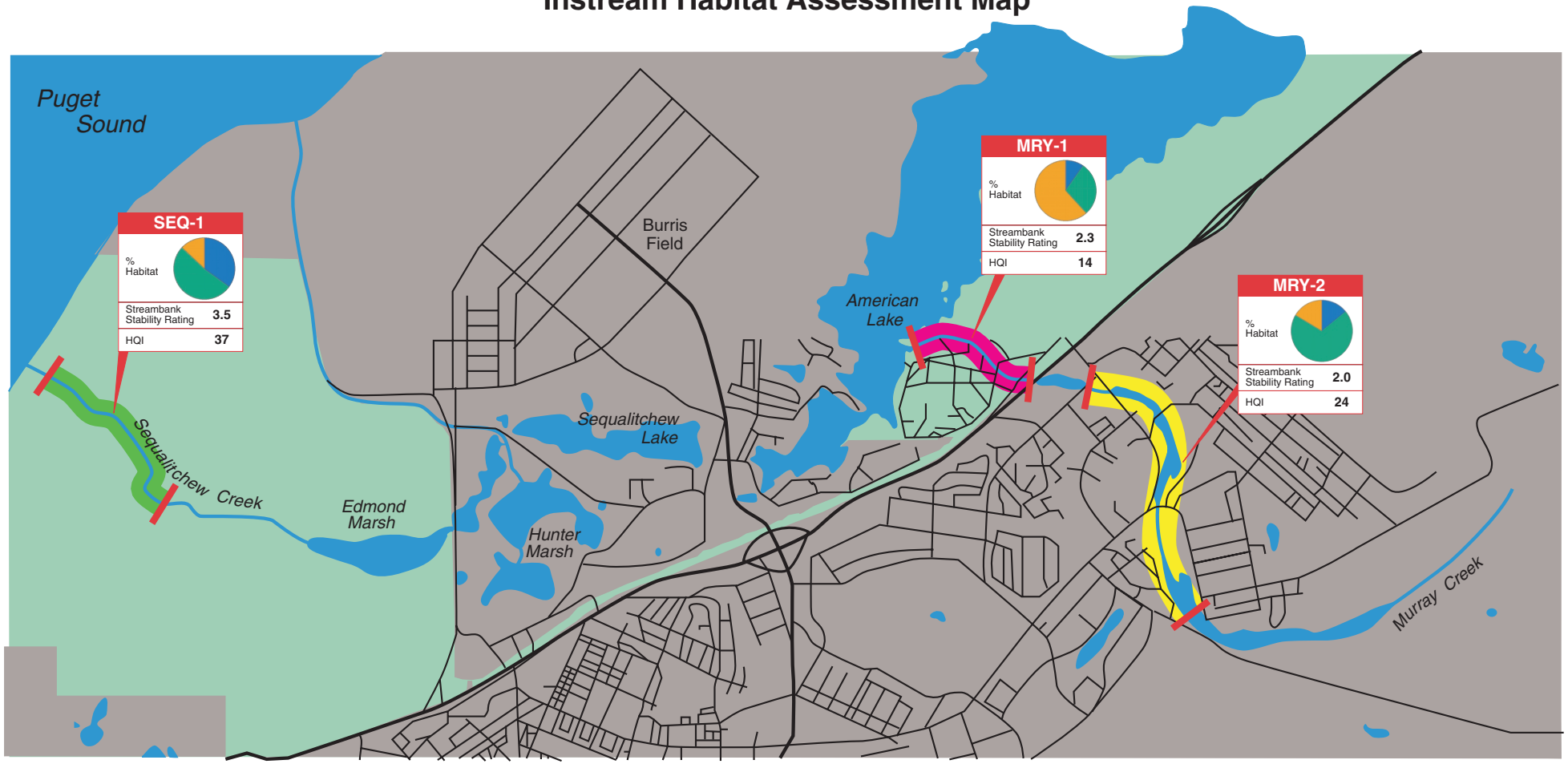
SEQ-1

See Map Legend H-9 for explanation

N W E S

0 0.5 1 miles

Fort Lewis
Sequalitchew and Murray Creeks
Instream Habitat Assessment Map



LEGEND

- Base
- Off Base
- Streams, lakes and wetlands
- Roads
- Survey reach location

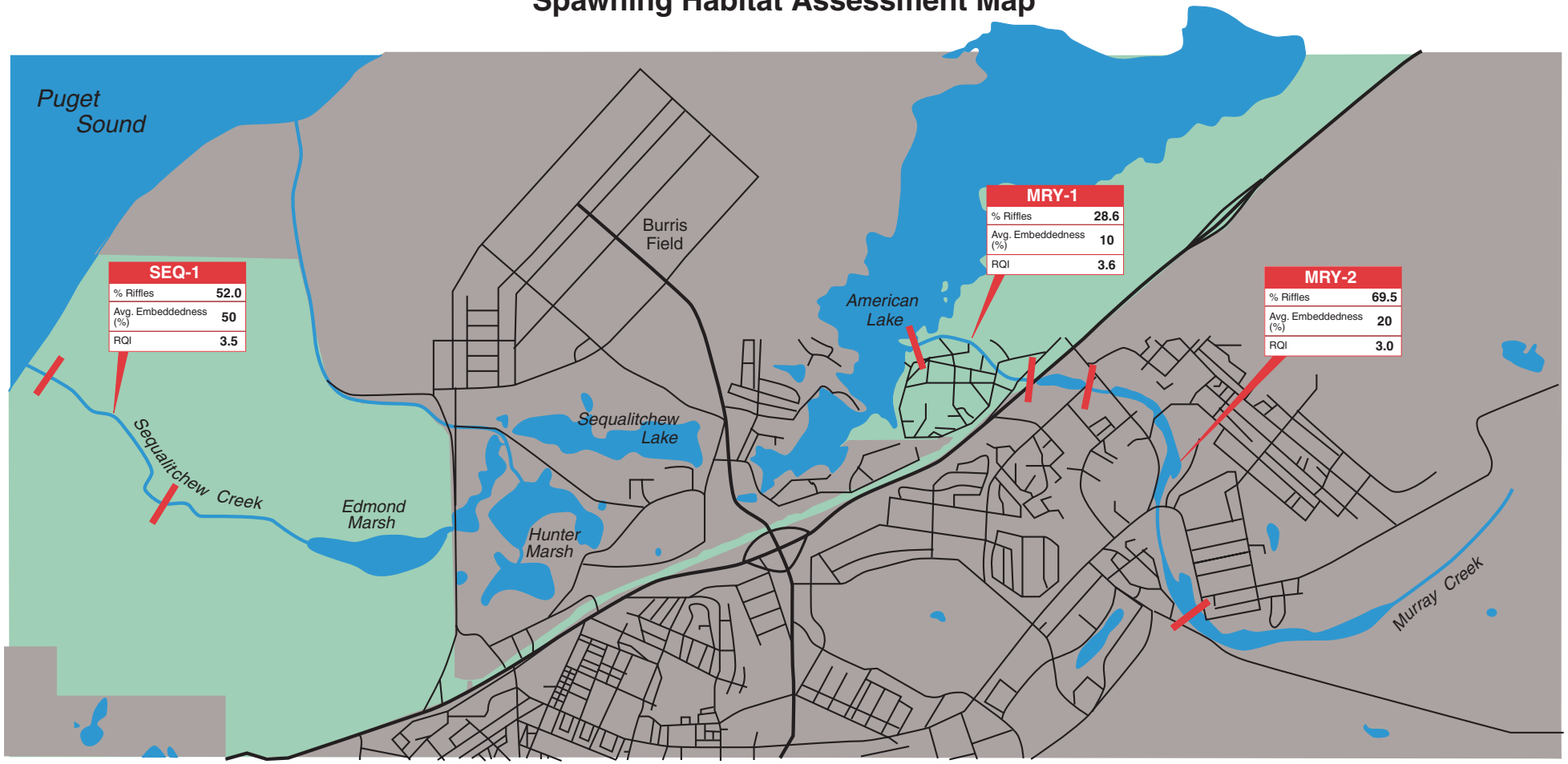
SEQ-1

See Map Legend H-9 for explanation

N W E S

0 0.5 1
miles

Fort Lewis
Sequalitchew and Murray Creeks
Spawning Habitat Assessment Map



LEGEND

- Base
- Off Base
- Streams, lakes and wetlands
- Roads
- Survey reach location

SEQ-1

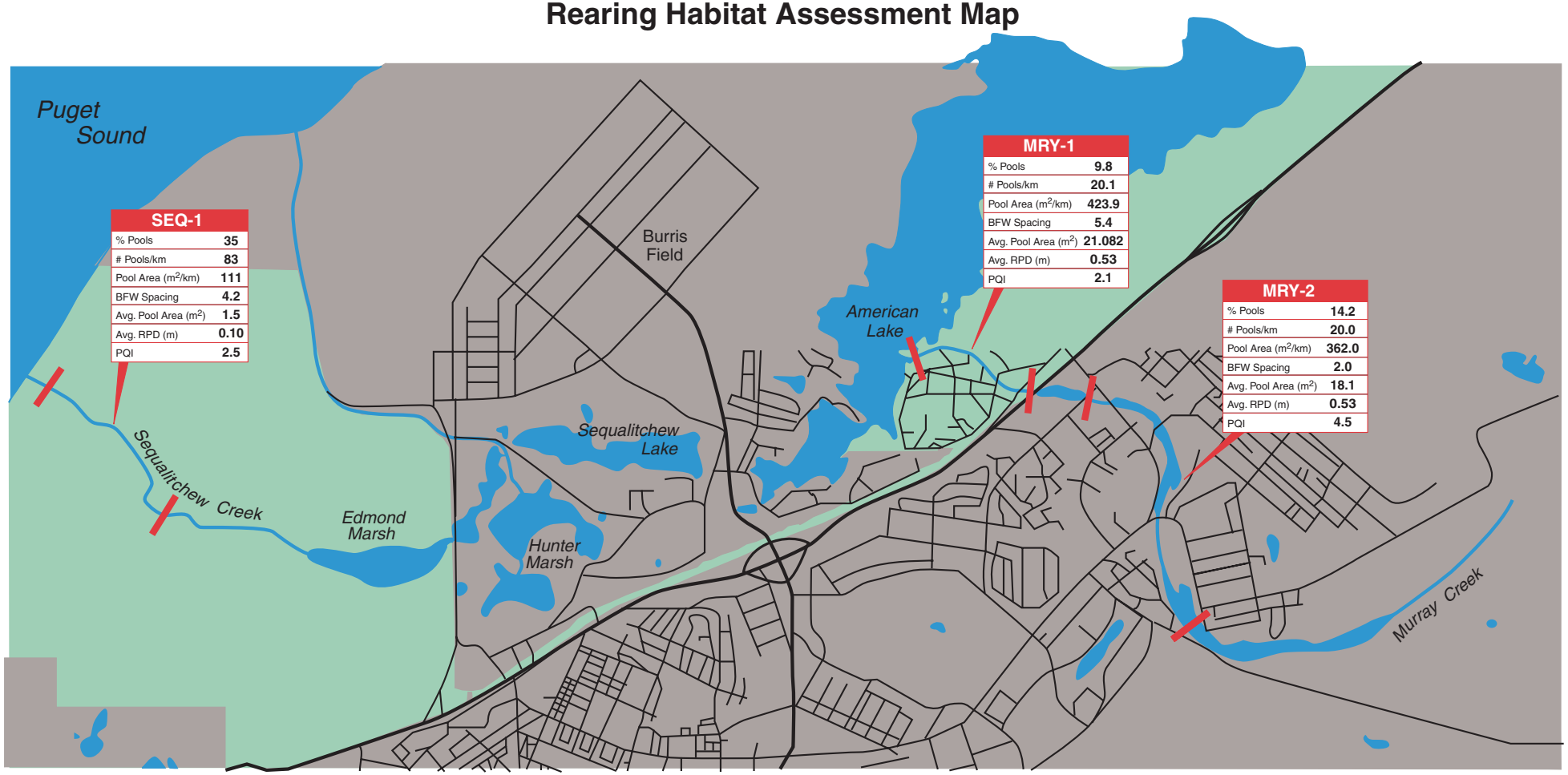
SEQ-1
% Riffles 52.0
Avg. Embeddedness (%) 50
RQI 3.5

See Map Legend H-9 for explanation

N W E S

0 0.5 1
miles

Fort Lewis
Sequalitchew and Murray Creeks
Rearing Habitat Assessment Map



LEGEND

- Base
- Off Base
- Streams, lakes and wetlands
- Roads
- Survey reach location

SEQ-1

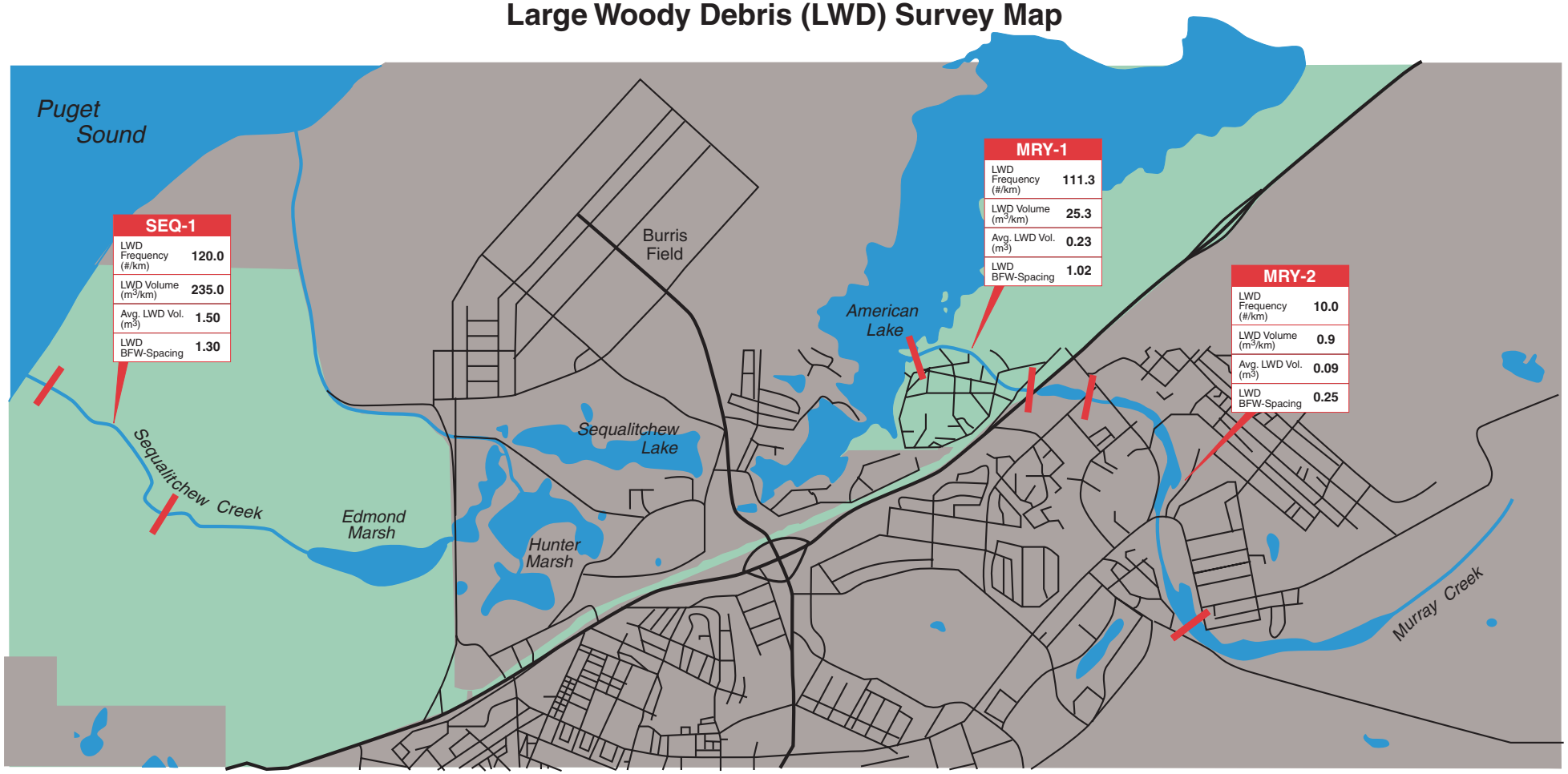
SEQ-1	
% Pools	35
# Pools/km	83
Pool Area (m2/km)	111
BFW Spacing	4.2
Avg. Pool Area (m2)	1.5
Avg. RPD (m)	0.10
PQI	2.5

See Map Legend H-9 for explanation

N W E S

0 0.5 1
miles

Fort Lewis
Sequalitchew and Murray Creeks
Large Woody Debris (LWD) Survey Map



LEGEND

- Base
- Off Base
- Streams, lakes and wetlands
- Roads
- Survey reach location

SEQ-1

See Map Legend H-9 for explanation

N W E S

0 0.5 1 miles

Map H-7

Fort Lewis
Sequalitchew and Murray Creeks
Biological Monitoring Site Map

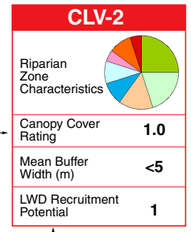
LEGEND

- Base
- Off Base
- Streams, lakes and wetlands
- Roads
- Bio-monitoring site

N W E S

0 0.5 1
miles

RIPARIAN CONDITIONS LEGEND



Survey Reach Identification

Relative Percentages of Riparian Zone Characteristics:

- Mature Coniferous
- Young Coniferous
- Mature Deciduous
- Young Deciduous
- Mixed Mature
- Mixed Young
- Prairie
- Woody Shrubs
- Herbaceous Tall
- Herbaceous Short
- Landscaped
- Lawn/Turf
- Impervious

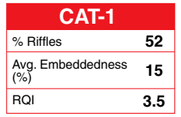
Canopy Cover Rating

80-100% Canopy Cover = 4
60-80% Canopy Cover = 3
40-60% Canopy Cover = 2
0-40% Canopy Cover = 1

LWD Recruitment Potential

Mature Coniferous Riparian w/adequate LWD = 4
Mixed Mature Riparian or w/o adequate LWD = 3
Mature Deciduous Riparian and/or w/o adequate LWD = 2
Lack of Riparian Forest & w/o adequate LWD = 1

SPAWNING HABITAT LEGEND



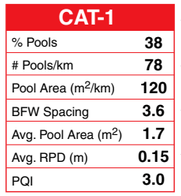
Survey Reach Identification

% Total Instream Habitat (Surface Area) in Riffles (40-60% is optimum)

Average Substrata Embeddedness (<10% is optimum)

Riffle Quality Index = Qualitative Rating of Spawning Habitat Quality (5 = excellent quality and 1 = poor quality)

REARING HABITAT LEGEND



Survey Reach Identification

% Total Instream Habitat (Surface Area) in Pools (40-60% is optimum)

Pool Frequency per km of Stream

Pool Area per km of Stream

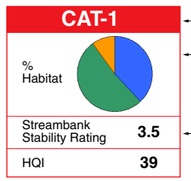
Bankfull-Width Spacings Between Pools (≤2 is optimum)

Average Area of Pools within Survey Reach

Average Residual Pool Depth

Pool Quality Index = A Qualitative Rating of Rearing Habitat Quality (5 = excellent quality and 1 = poor quality)

INSTREAM HABITAT CONDITIONS LEGEND



Survey Reach Identification

Relative Percentages of Instream Habitat Characteristics: % Pool % Riffle % Glide

Streambank Stability Rating

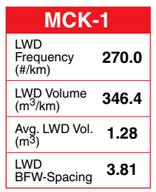
75-100% Stable/Vegetated = 4
50-75% Stable/Vegetated = 3
25-50% Stable/Vegetated = 2
0-25% Stable/Vegetated = 1

HQI Score

>40	Excellent	
30-40	Good	
20-30	Fair	
<20	Poor	

Shown along respective surveyed reach

LARGE WOODY DEBRIS (LWD) LEGEND



Survey Reach Identification

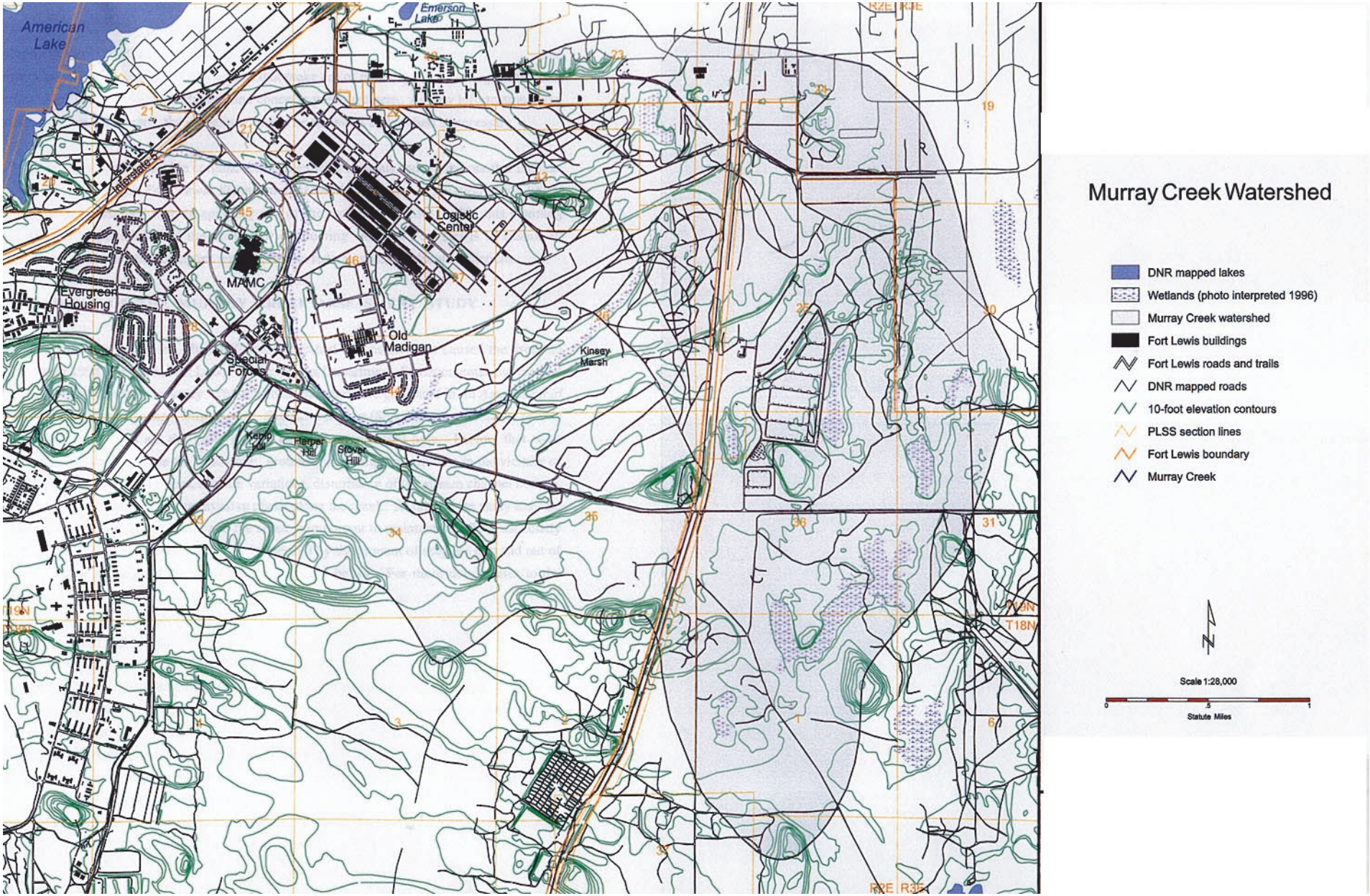
Frequency of LWD within Survey Reach

Volume of LWD within Survey Reach

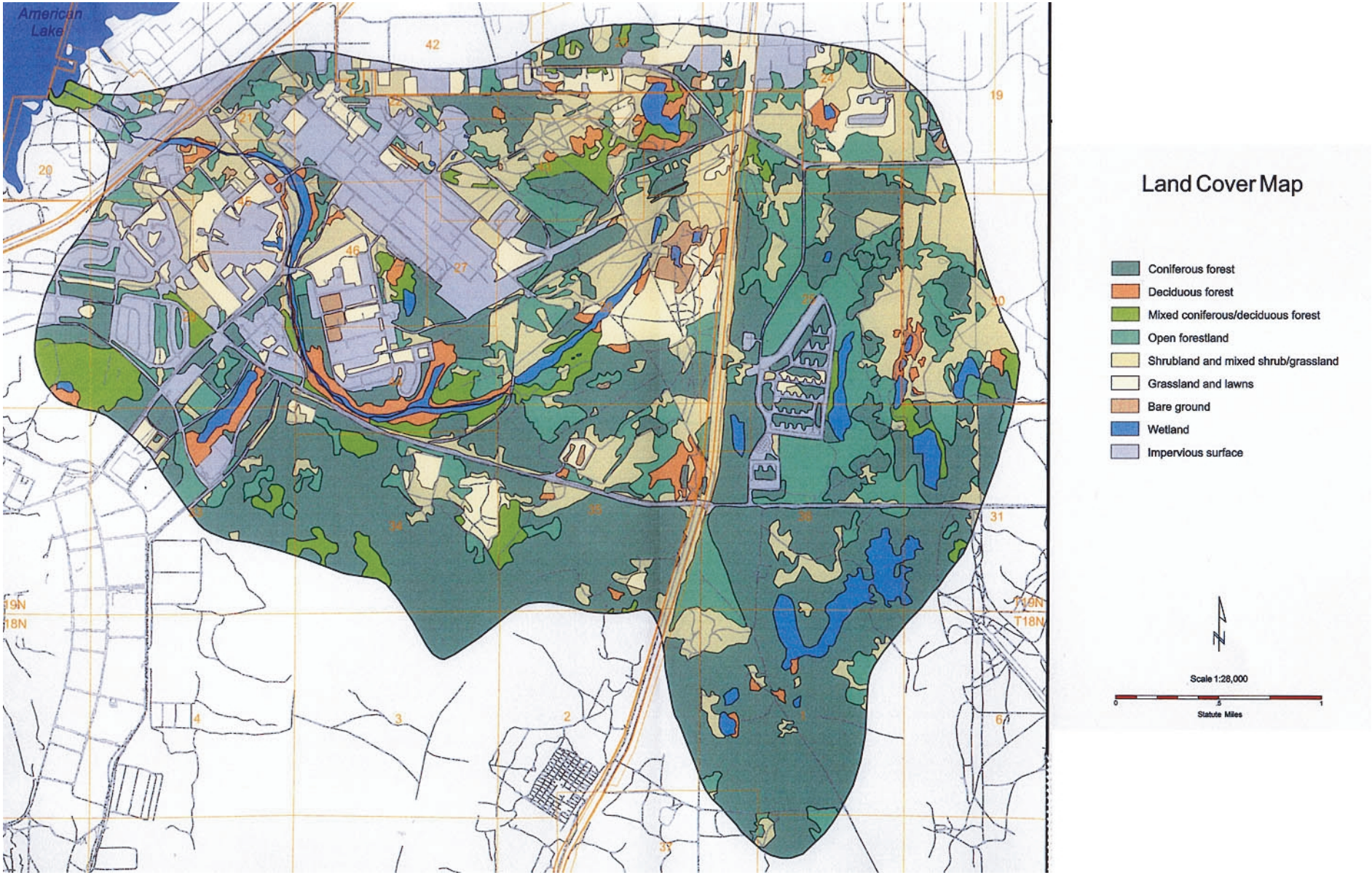
Average Volume (size) of LWD within Survey Reach

Pieces of LWD per Bankfull-Width Spacing (≥2 is optimum)

Murray Creek Watershed Map
(Fort Lewis, 1996)

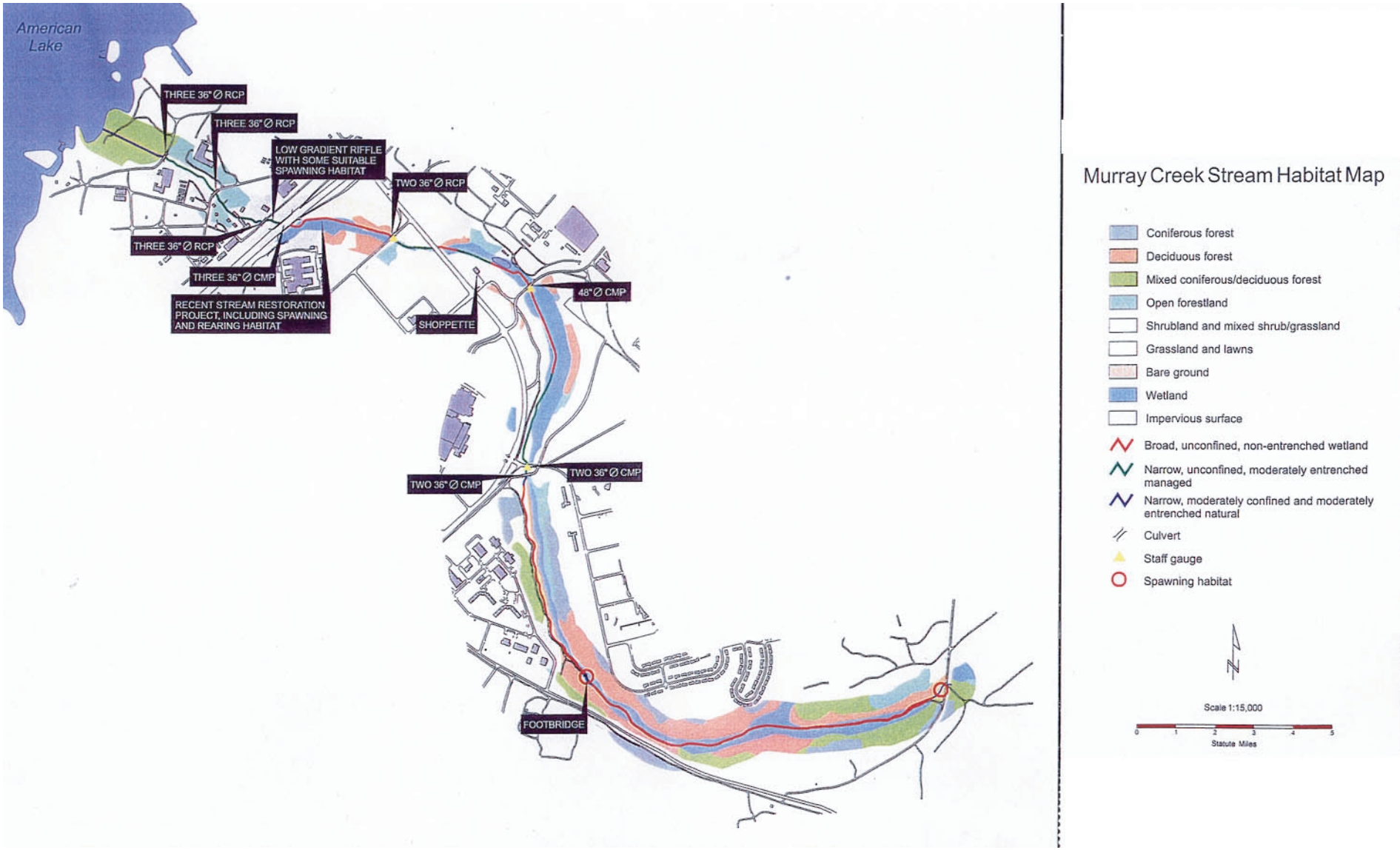


Murray Creek Land-Cover Map
(Fort Lewis, 1996)

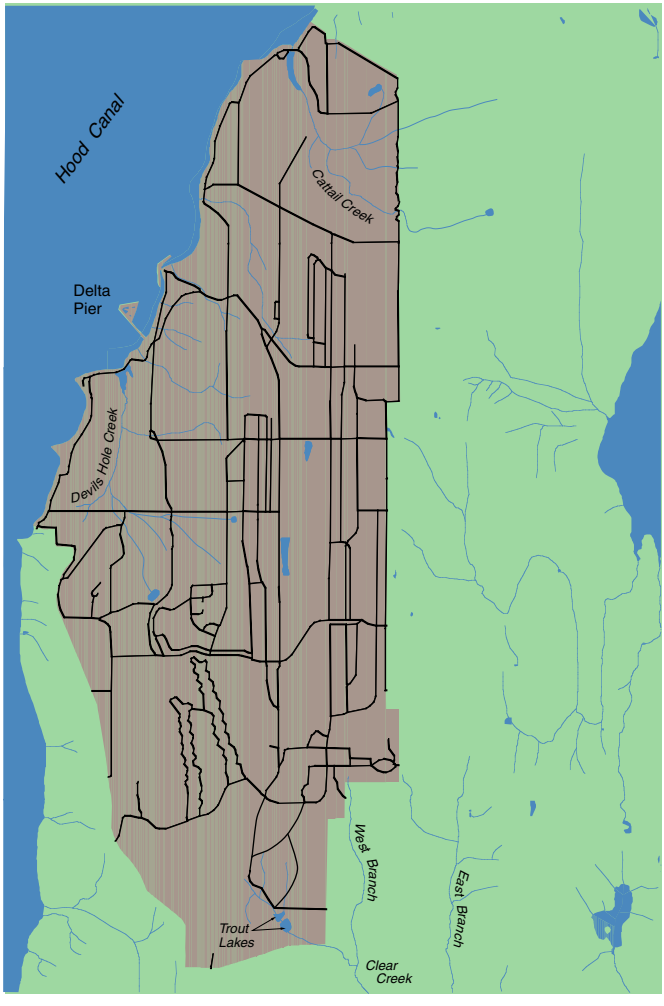


Murray Creek Water Resources Protection Zone Map
(Fort Lewis, 1996)

Murray Creek Habitat Map
(Fort Lewis, 1996)



Naval Submarine Base (NSB) Bangor
Base Map



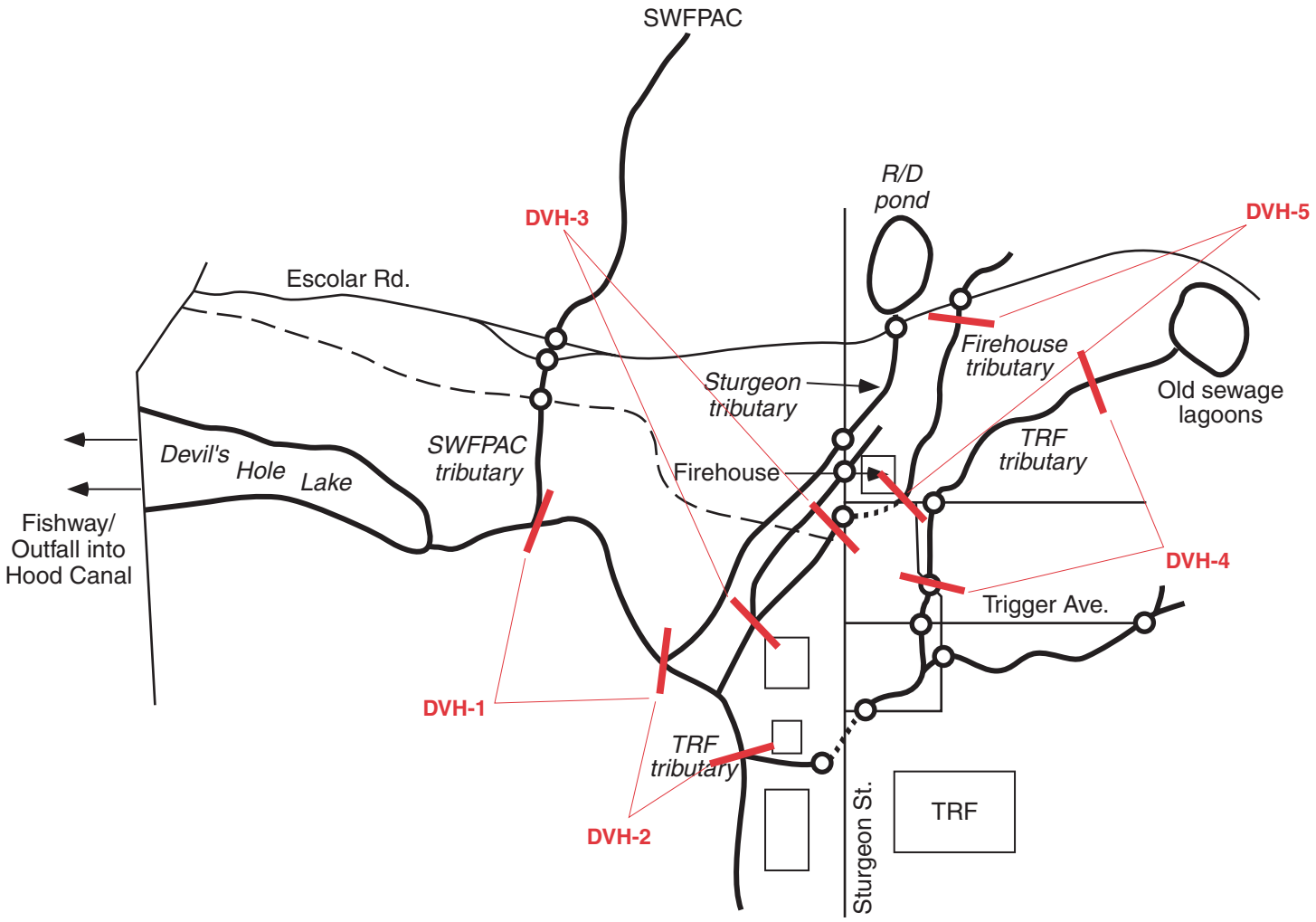
LEGEND

- Base
- Off Base
- Streams, lakes and wetlands
- Roads

N
W E
S

0 0.5 1
miles

Naval Submarine Base (NSB) Bangor
Devils Hole Creek
Stream Survey Reach Map



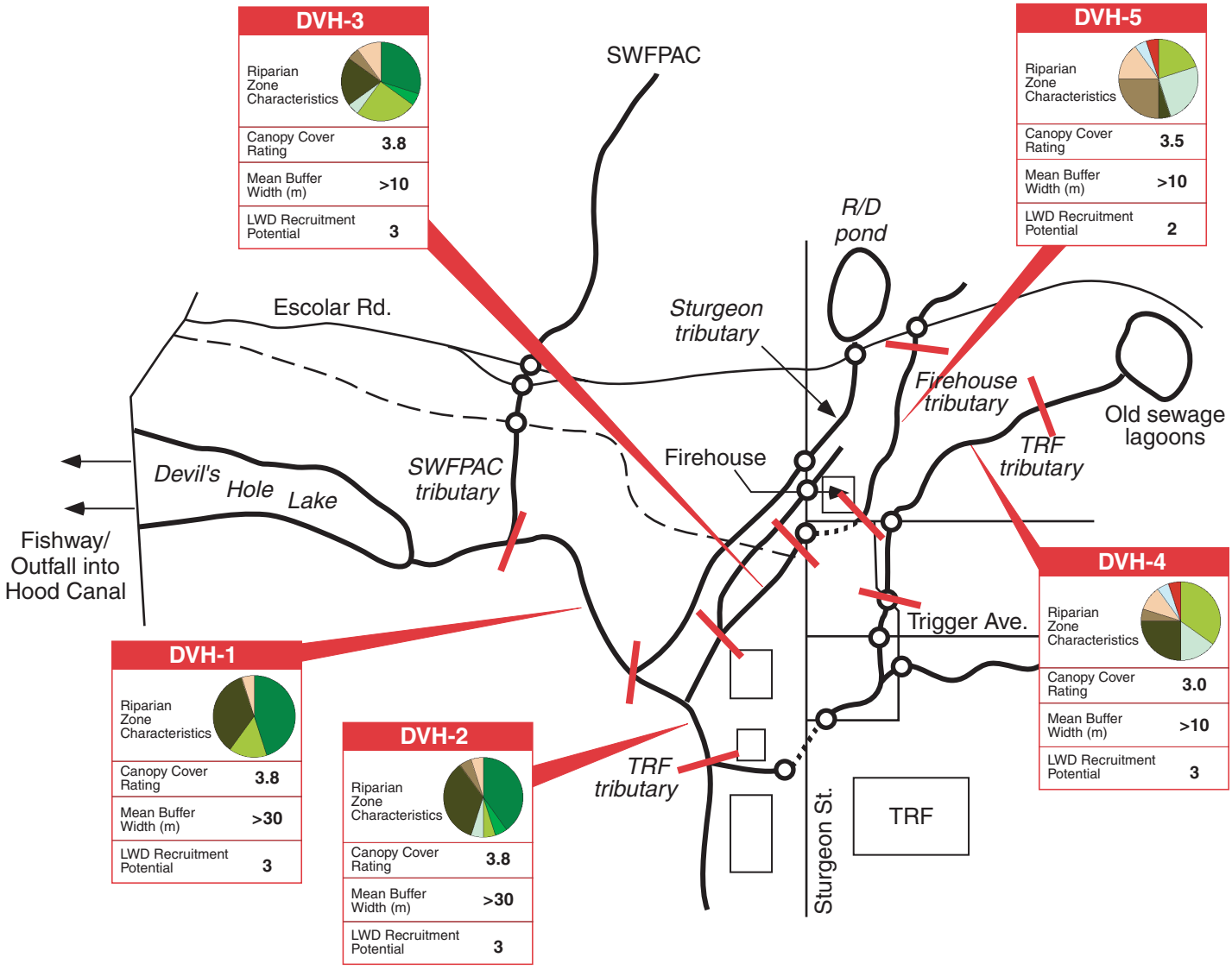
LEGEND

- Culvert
- Road
- Trail/utility line
- Streams, lakes and wetlands
- Survey reach location (DVH-1)

(no scale)

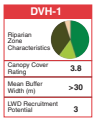
N W E S

Naval Submarine Base (NSB) Bangor
Devils Hole Creek
Riparian Conditions Map



LEGEND

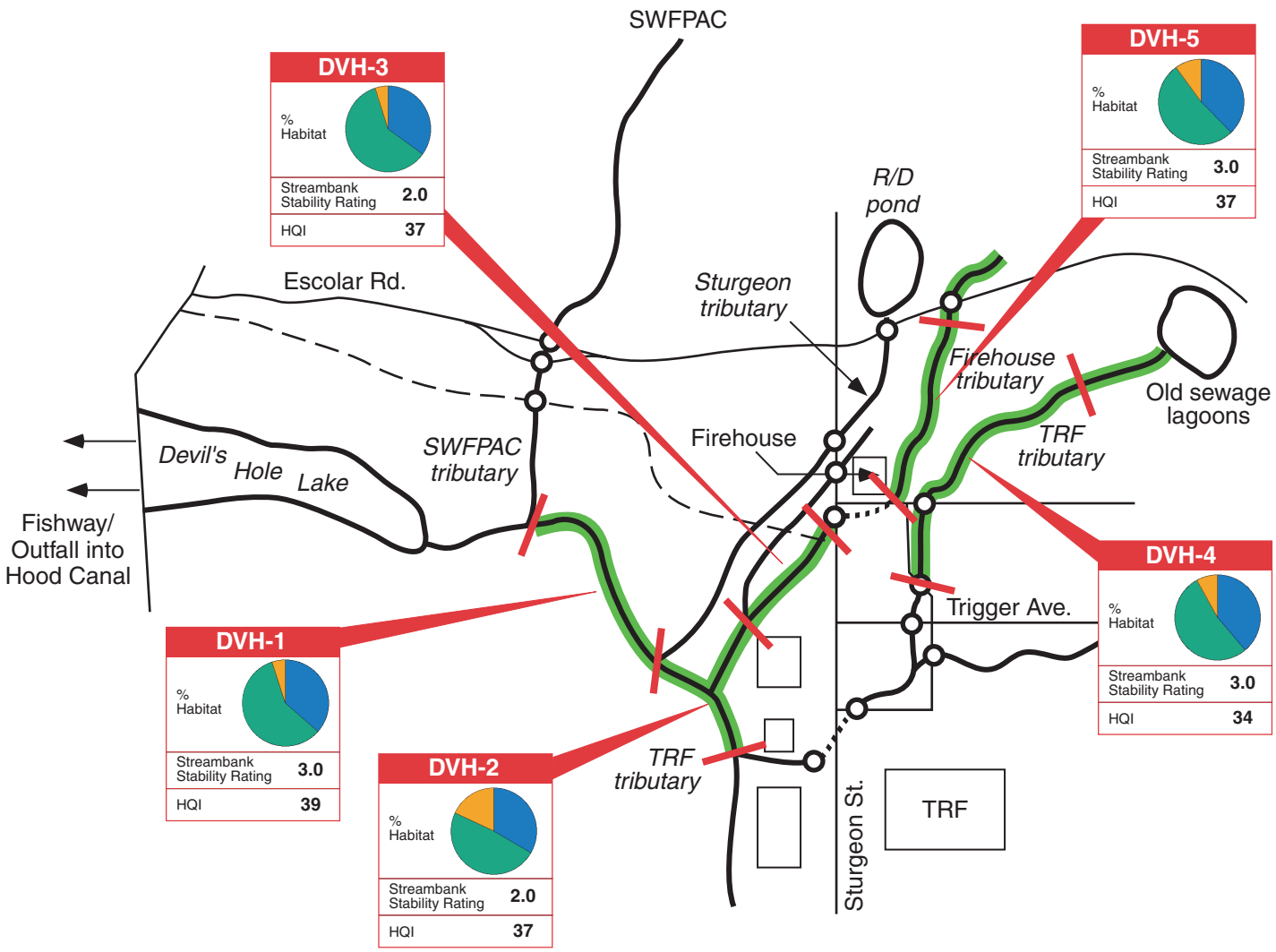
- Culvert
- Road
- Trail/utility line
- Streams, lakes and wetlands
- Survey reach location (DVH-1)



See Map Legend I-9 for explanation

(no scale)

Naval Submarine Base (NSB) Bangor
Devils Hole Creek
Instream Habitat Assessment Map



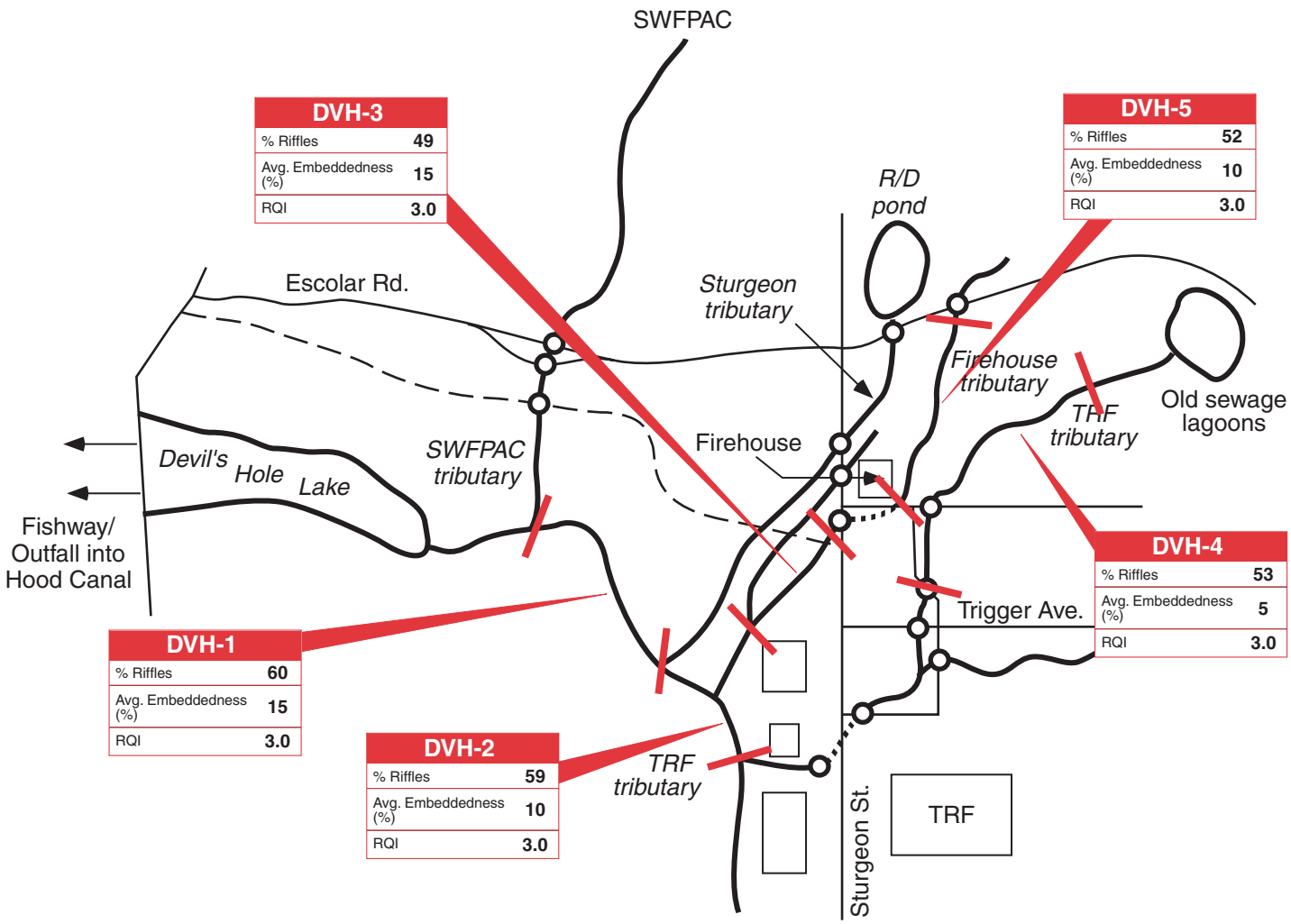
LEGEND

- Culvert
- Road
- Trail/utility line
- Streams, lakes and wetlands
- Survey reach location (DVH-1)
- *See Map Legend I-9 for explanation*

(no scale)

N W E S

Naval Submarine Base (NSB) Bangor
Devils Hole Creek
Spawning Habitat Assessment Map



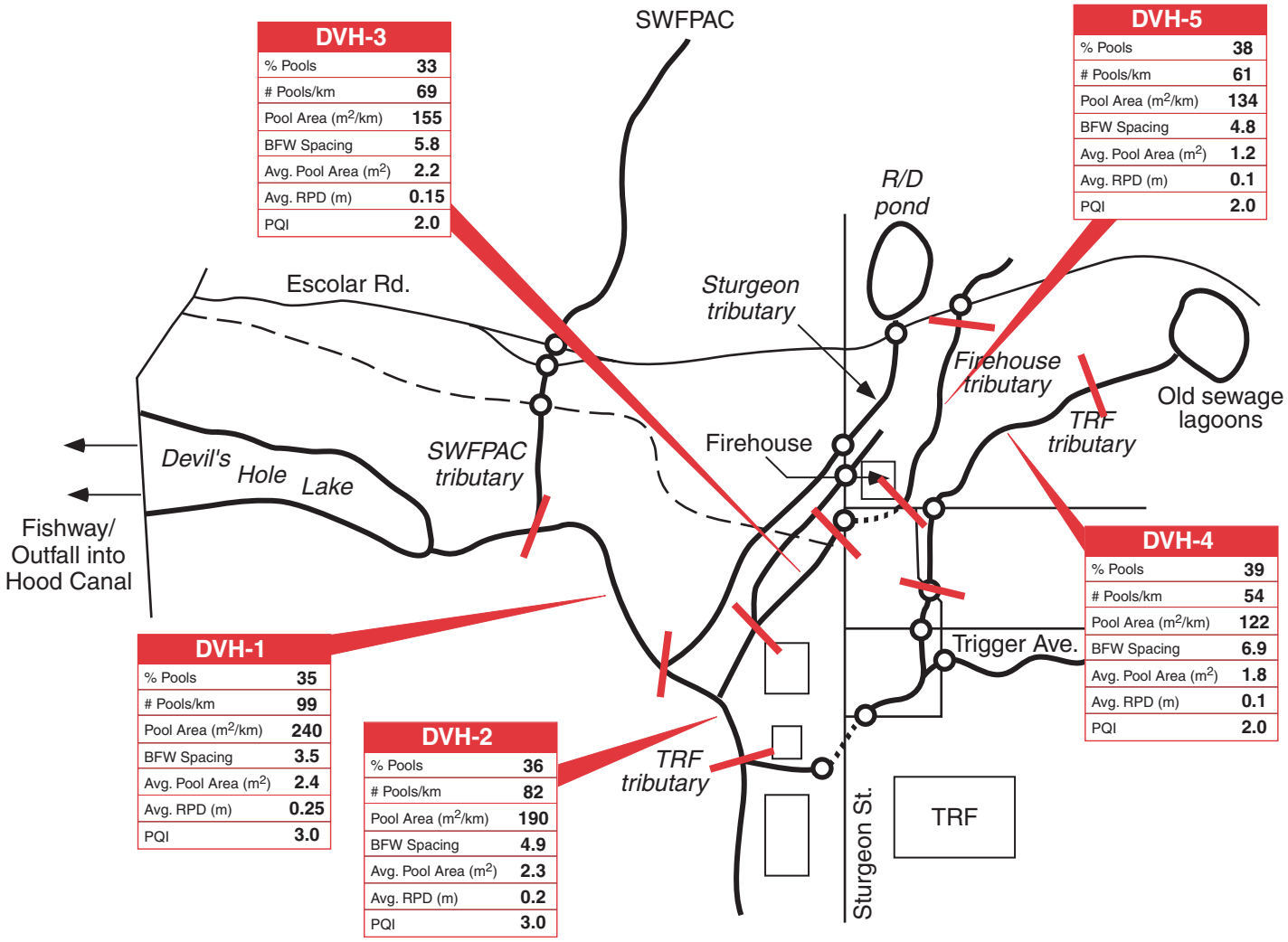
LEGEND

- Culvert
- Road
- Trail/utility line
- Streams, lakes and wetlands
- DVH-1 — Survey reach location
- DVH-1 (% Riffles 60; Avg. Embeddedness (%) 15; RQI 3.0) — *See Map Legend I-9 for explanation*

(no scale)

N W E S

Naval Submarine Base (NSB) Bangor
Devils Hole Creek
Rearing Habitat Assessment Map



DVH-3	
% Pools	33
# Pools/km	69
Pool Area (m^2/km)	155
BFW Spacing	5.8
Avg. Pool Area (m^2)	2.2
Avg. RPD (m)	0.15
PQI	2.0

DVH-5	
% Pools	38
# Pools/km	61
Pool Area (m^2/km)	134
BFW Spacing	4.8
Avg. Pool Area (m^2)	1.2
Avg. RPD (m)	0.1
PQI	2.0

DVH-4	
% Pools	39
# Pools/km	54
Pool Area (m^2/km)	122
BFW Spacing	6.9
Avg. Pool Area (m^2)	1.8
Avg. RPD (m)	0.1
PQI	2.0

DVH-1	
% Pools	35
# Pools/km	99
Pool Area (m^2/km)	240
BFW Spacing	3.5
Avg. Pool Area (m^2)	2.4
Avg. RPD (m)	0.25
PQI	3.0

DVH-2	
% Pools	36
# Pools/km	82
Pool Area (m^2/km)	190
BFW Spacing	4.9
Avg. Pool Area (m^2)	2.3
Avg. RPD (m)	0.2
PQI	3.0

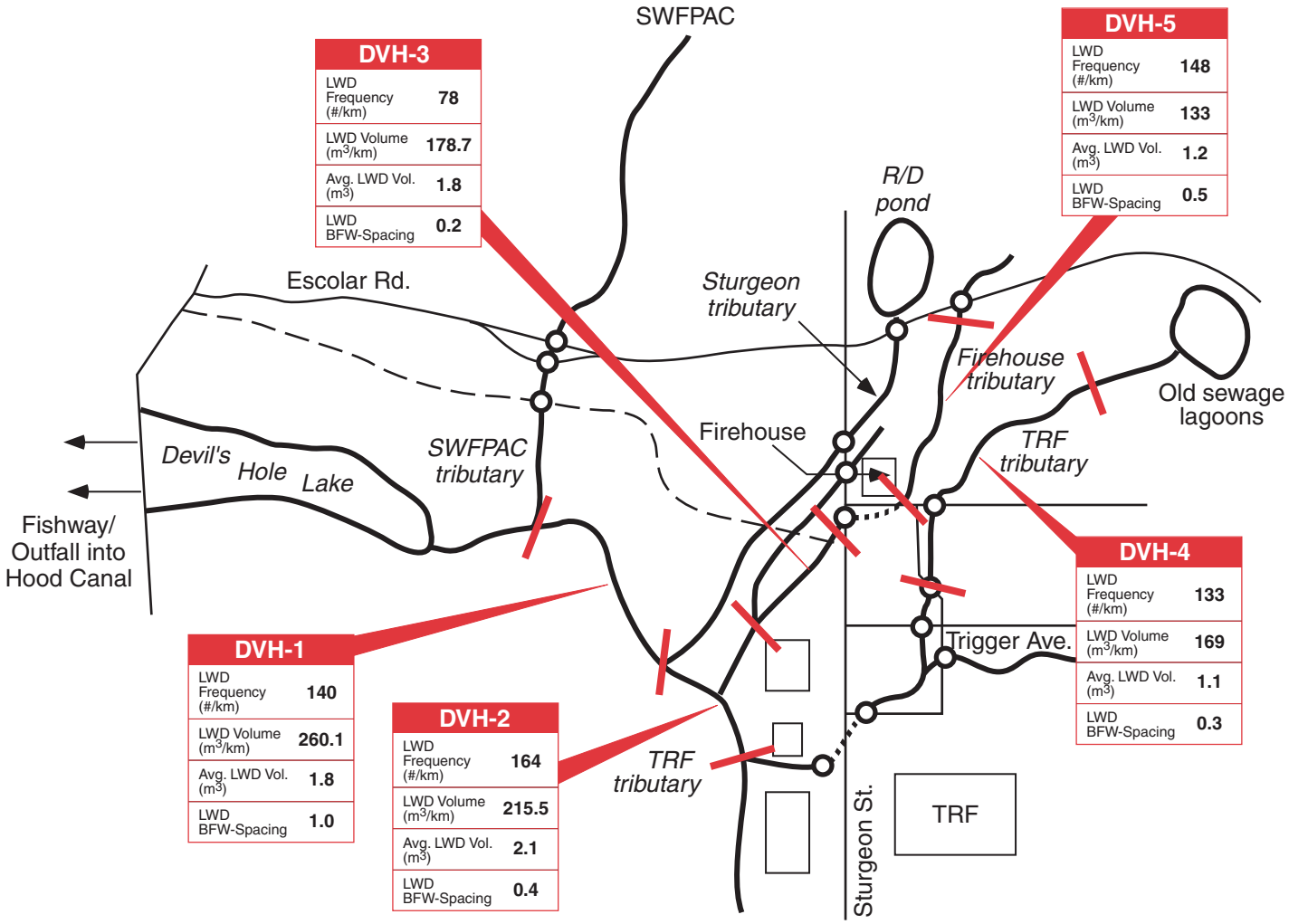
LEGEND

- Culvert
- Road
- Trail/utility line
- Streams, lakes and wetlands
- Survey reach location (DVH-1)
- *See Map Legend I-9 for explanation*

(no scale)

N W E S

Naval Submarine Base (NSB) Bangor
Devils Hole Creek
Large Woody Debris (LWD) Survey Map



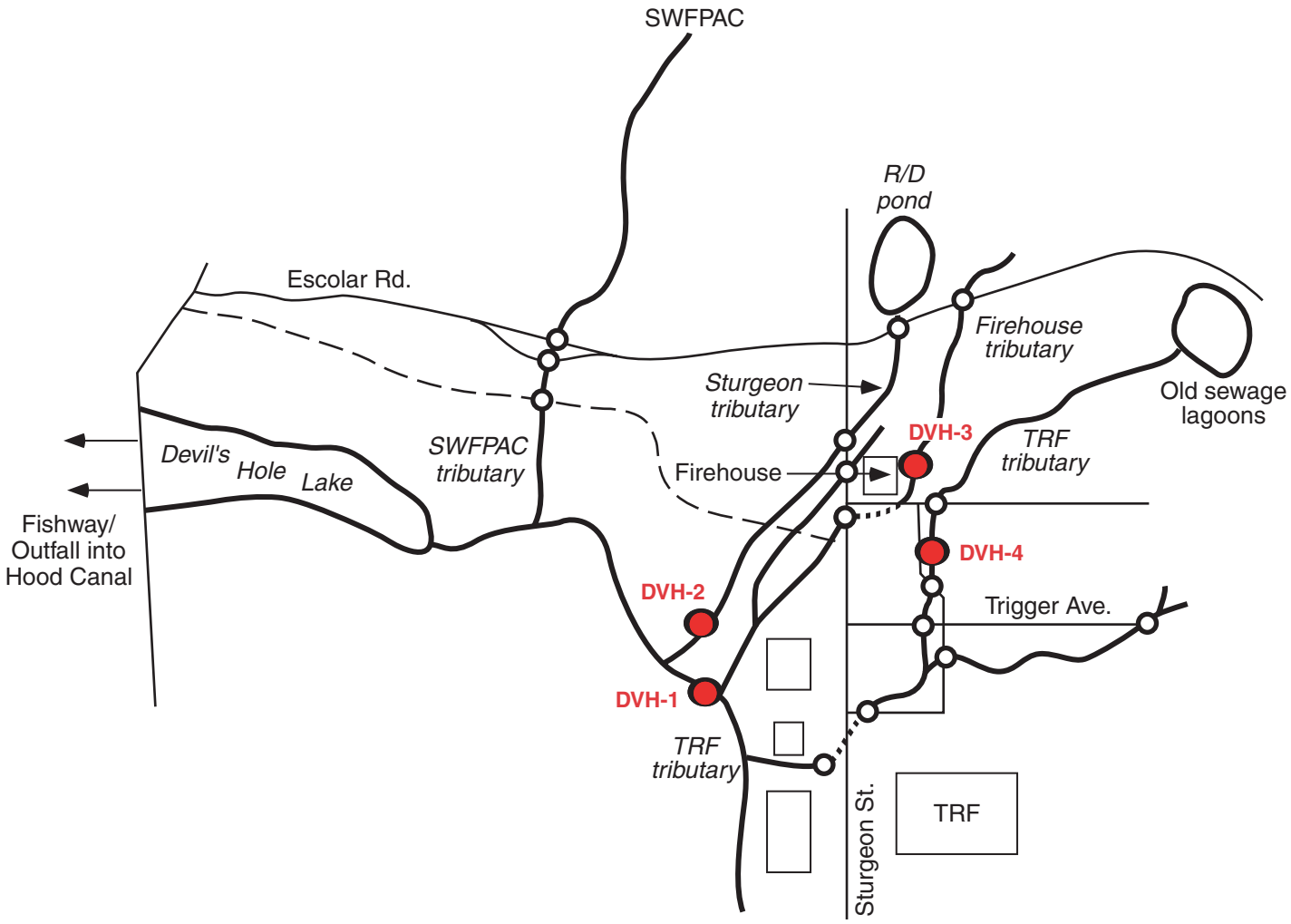
LEGEND

- Culvert
- Road
- Trail/utility line
- Streams, lakes and wetlands
- DVH-1 — Survey reach location
- DVH-1 (LWD Frequency (#/km) 140; LWD Volume (m^3/km) 260.1; Avg. LWD Vol. (m^3) 1.8; LWD BFW-Spacing 1.0) — *See Map Legend I-9 for explanation*

(no scale)

N W E S

Naval Submarine Base (NSB) Bangor
Devils Hole Creek
Biological Monitoring Site Map



LEGEND

- Culvert
- Road
- Trail/utility line
- Streams, lakes and wetlands
- Bio-monitoring site

(no scale)

N
W E
S

RIPARIAN CONDITIONS LEGEND

CLV-2	
Riparian Zone Characteristics	
Canopy Cover Rating	1.0
Mean Buffer Width (m)	<5
LWD Recruitment Potential	1

Survey Reach Identification

Relative Percentages of Riparian Zone Characteristics:

- Mature Coniferous
- Young Coniferous
- Mature Deciduous
- Young Deciduous
- Mixed Mature
- Mixed Young
- Prairie
- Woody Shrubs
- Herbaceous Tall
- Herbaceous Short
- Landscaped
- Lawn/Turf
- Impervious

Canopy Cover Rating

80-100% Canopy Cover = 4
60-80% Canopy Cover = 3
40-60% Canopy Cover = 2
0-40% Canopy Cover = 1

LWD Recruitment Potential

Mature Coniferous Riparian w/adequate LWD = 4
Mixed Mature Riparian or w/o adequate LWD = 3
Mature Deciduous Riparian and/or w/o adequate LWD = 2
Lack of Riparian Forest & w/o adequate LWD = 1

SPAWNING HABITAT LEGEND

CAT-1	
% Riffles	52
Avg. Embeddedness (%)	15
RQI	3.5

% Total Instream Habitat (Surface Area) in Riffles (40-60% is optimum)

Riffle Quality Index = Qualitative Rating of Spawning Habitat Quality (5 = excellent quality and 1 = poor quality)

Survey Reach Identification

Average Substrata Embeddedness (<10% is optimum)

REARING HABITAT LEGEND

CAT-1	
% Pools	38
# Pools/km	78
Pool Area (m^2/km)	120
BFW Spacing	3.6
Avg. Pool Area (m^2)	1.7
Avg. RPD (m)	0.15
PQI	3.0

% Total Instream Habitat (Surface Area) in Pools (40-60% is optimum)

Pool Area per km of Stream

Average Area of Pools within Survey Reach

Pool Quality Index = A Qualitative Rating of Rearing Habitat Quality (5 = excellent quality and 1 = poor quality)

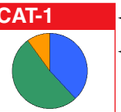
Survey Reach Identification

Pool Frequency per km of Stream

Bankfull-Width Spacings Between Pools (≤2 is optimum)

Average Residual Pool Depth

INSTREAM HABITAT CONDITIONS LEGEND

CAT-1	
% Habitat	
Streambank Stability Rating	3.5
HQI	39

Survey Reach Identification

Relative Percentages of Instream Habitat Characteristics: % Pool % Riffle % Glide

Streambank Stability Rating

75-100% Stable/Vegetated = 4
50-75% Stable/Vegetated = 3
25-50% Stable/Vegetated = 2
0-25% Stable/Vegetated = 1

HQI Score

>40	Excellent	
30-40	Good	
20-30	Fair	
<20	Poor	

Shown along respective surveyed reach

LARGE WOODY DEBRIS (LWD) LEGEND

MCK-1	
LWD Frequency (#/km)	270.0
LWD Volume (m^3/km)	346.4
Avg. LWD Vol. (m^3)	1.28
LWD BFW-Spacing	3.81

Survey Reach Identification

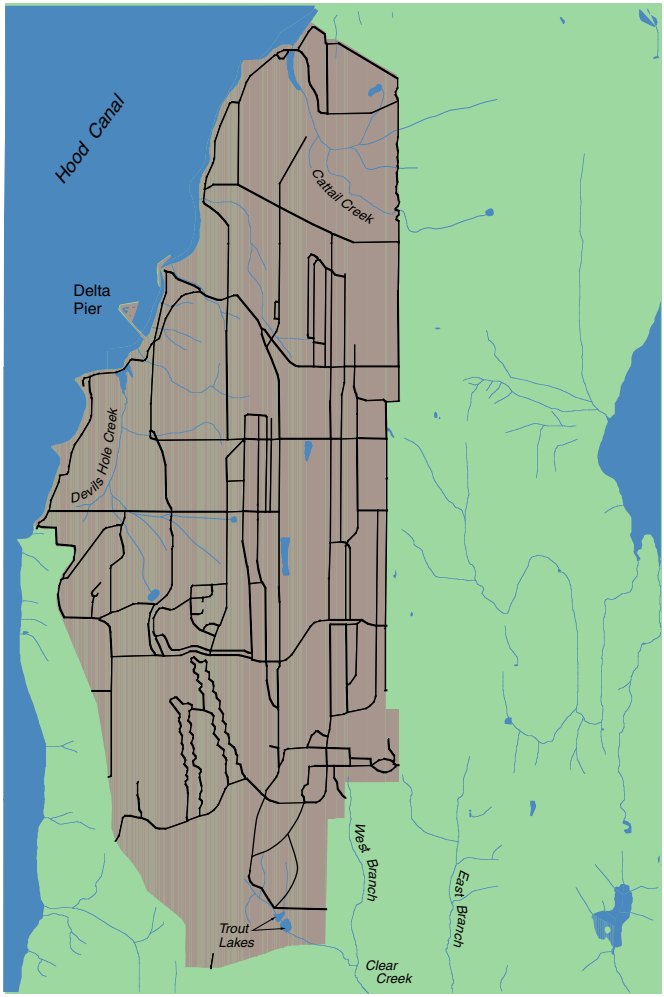
Frequency of LWD within Survey Reach

Volume of LWD within Survey Reach

Average Volume (size) of LWD within Survey Reach

Pieces of LWD per Bankfull-Width Spacing (≥2 is optimum)

Naval Submarine Base (NSB) Bangor
Base Map



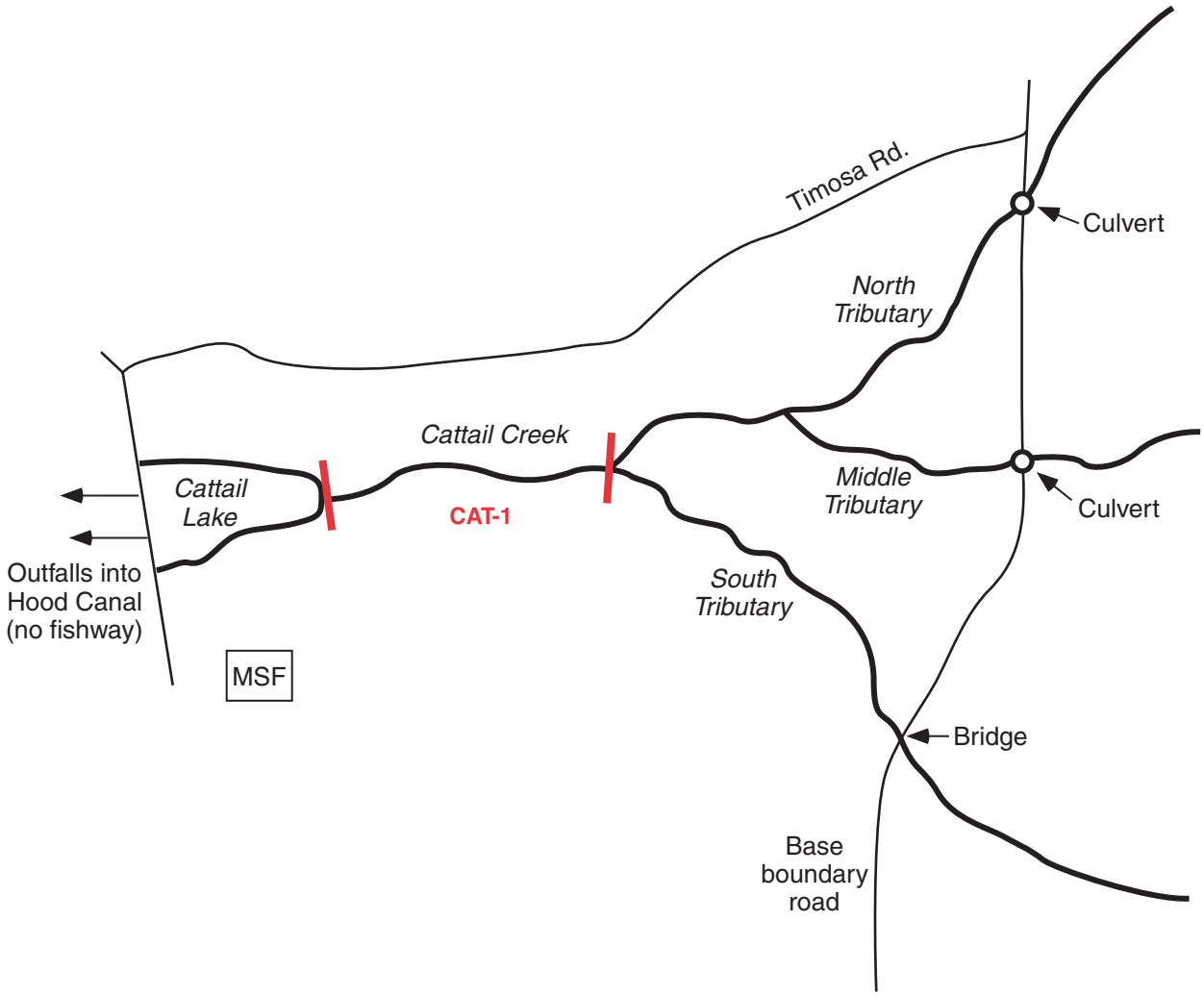
LEGEND

- Base
- Off Base
- Streams, lakes and wetlands
- Roads

N
W E
S

0 0.5 1
miles

Naval Submarine Base (NSB) Bangor
Cattail Creek
Stream Survey Reach Map



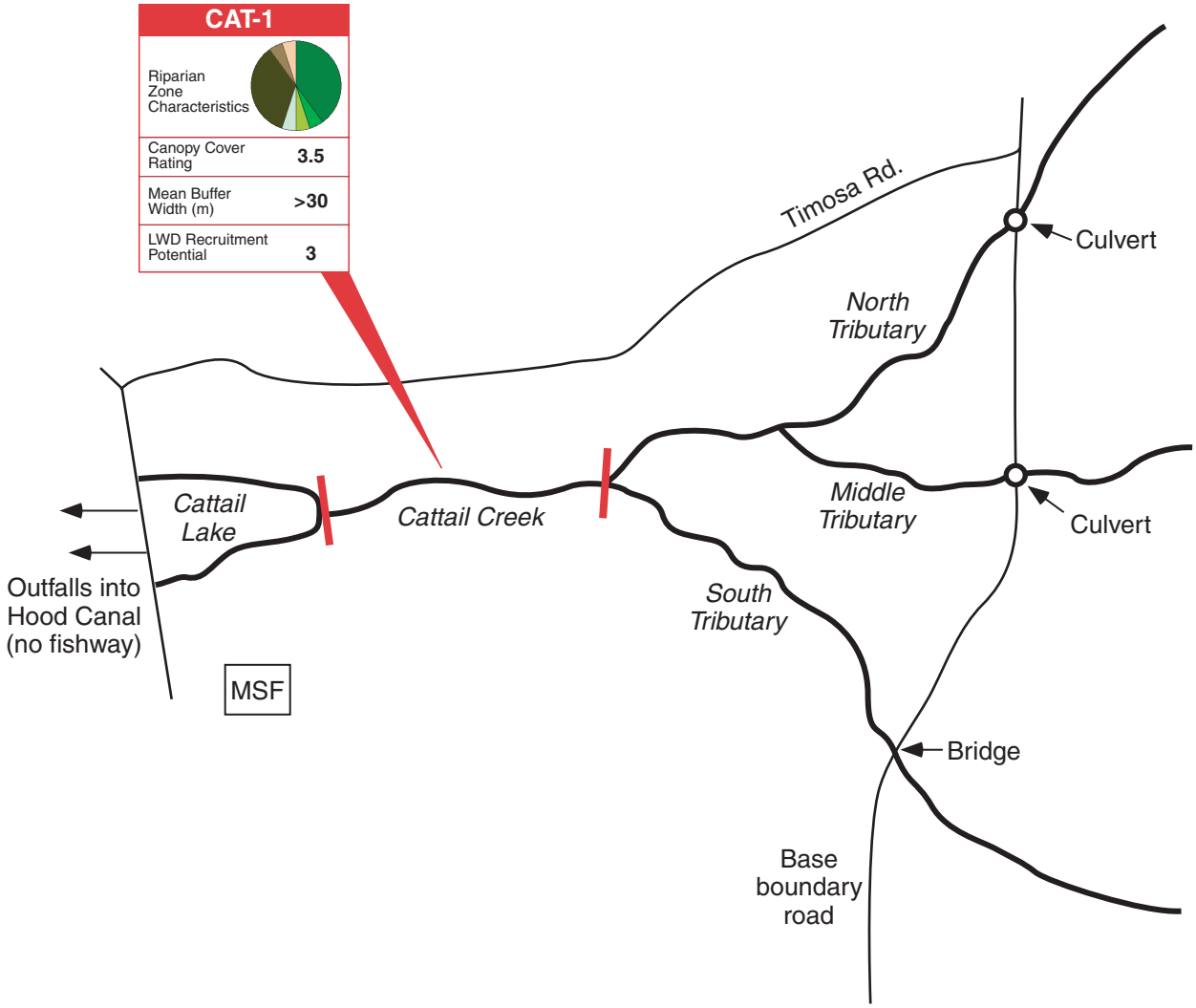
LEGEND

- Culvert
- Road
- Streams, lakes and wetlands
- Survey reach location (CAT-1)

(no scale)

N W E S

Naval Submarine Base (NSB) Bangor
Cattail Creek
Riparian Conditions Map



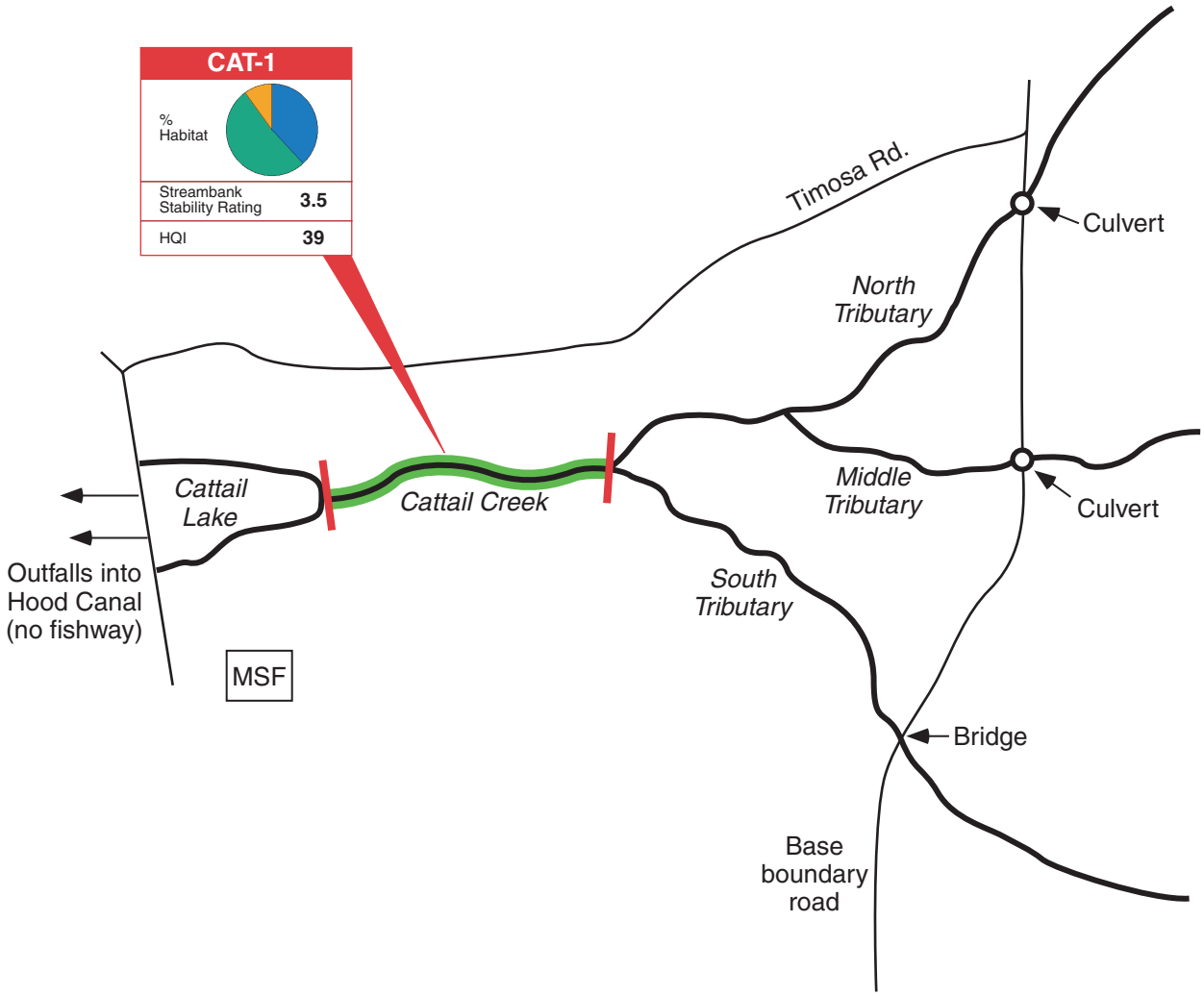
LEGEND

- Culvert
- Road
- Streams, lakes and wetlands
- Survey reach location (CAT-1)
- *See Map Legend J-9 for explanation*

(no scale)

N W E S

Naval Submarine Base (NSB) Bangor
Cattail Creek
Instream Habitat Assessment Map



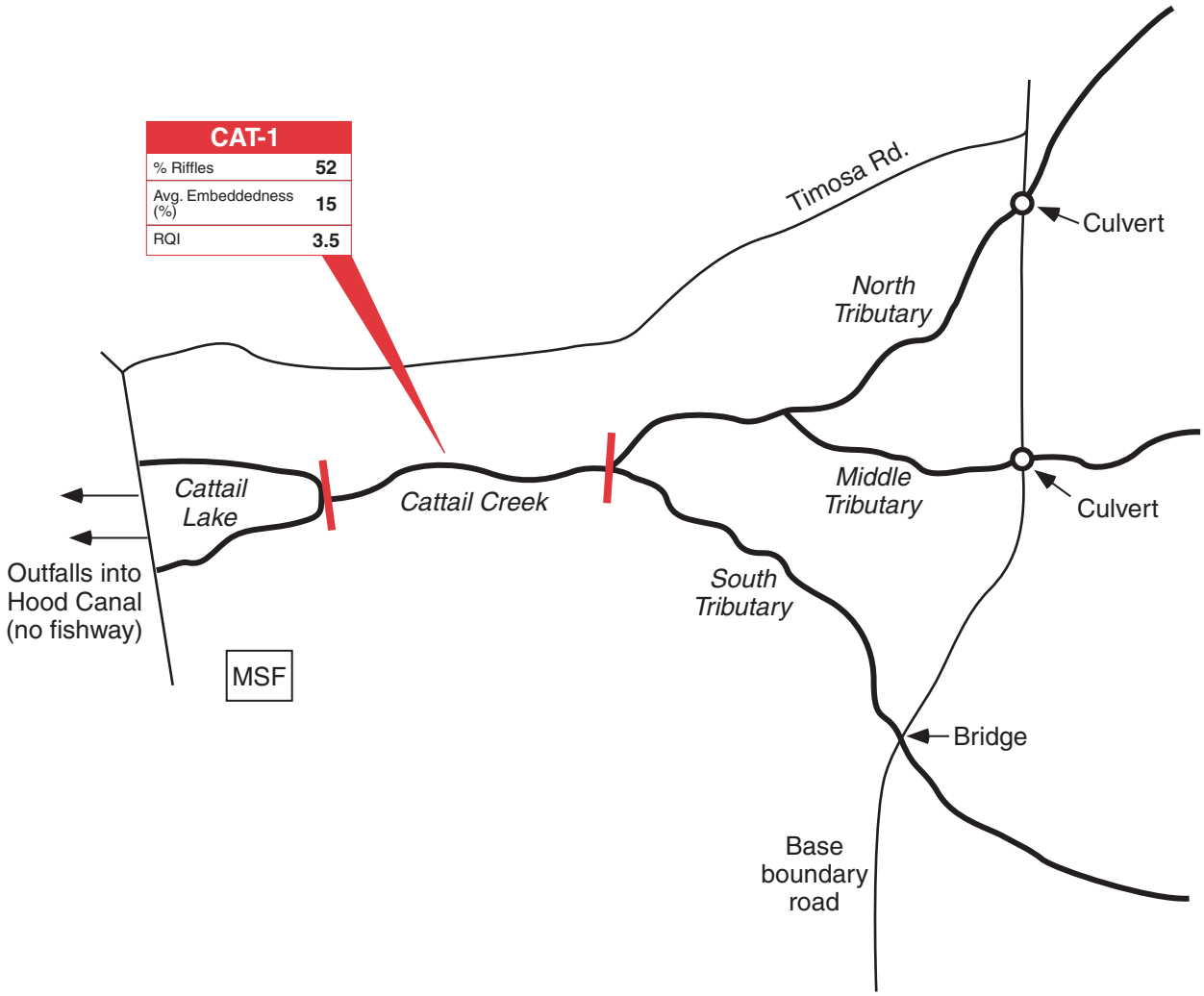
LEGEND

- Culvert
- Road
- Streams, lakes and wetlands
- Survey reach location (CAT-1)
- *See Map Legend J-9 for explanation*

(no scale)

N
W E
S

Naval Submarine Base (NSB) Bangor
Cattail Creek
Spawning Habitat Assessment Map



LEGEND

- Culvert
- Road
- Streams, lakes and wetlands
- Survey reach location (CAT-1)
- *See Map Legend J-9 for explanation*

(no scale)

N
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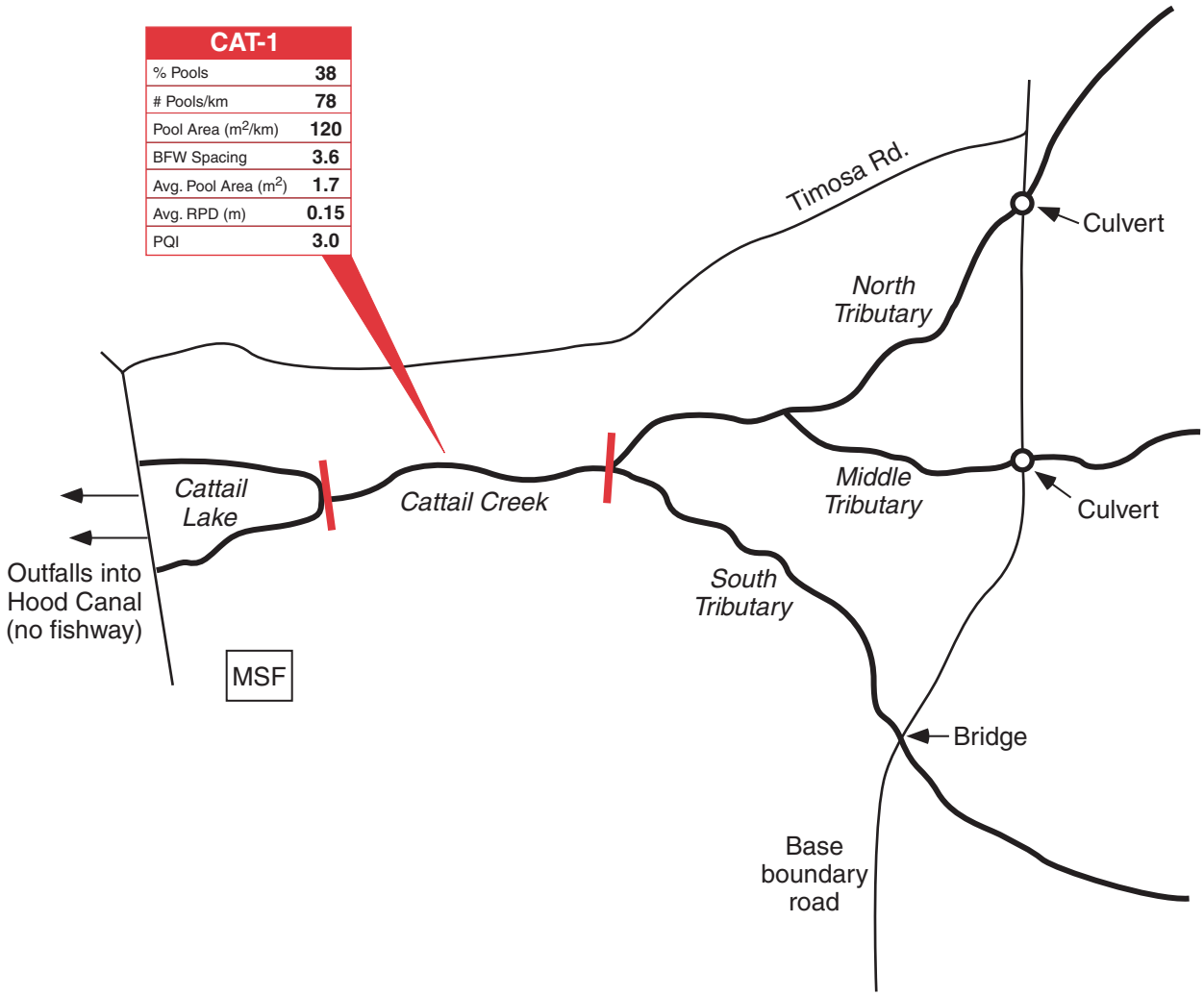
Naval Submarine Base (NSB) Bangor
Cattail Creek
Rearing Habitat Assessment Map



LEGEND

- Culvert
- Road
- Streams, lakes and wetlands
- Survey reach location (CAT-1)
- CAT-1 table — *See Map Legend J-9 for explanation*

(no scale)

N
W E
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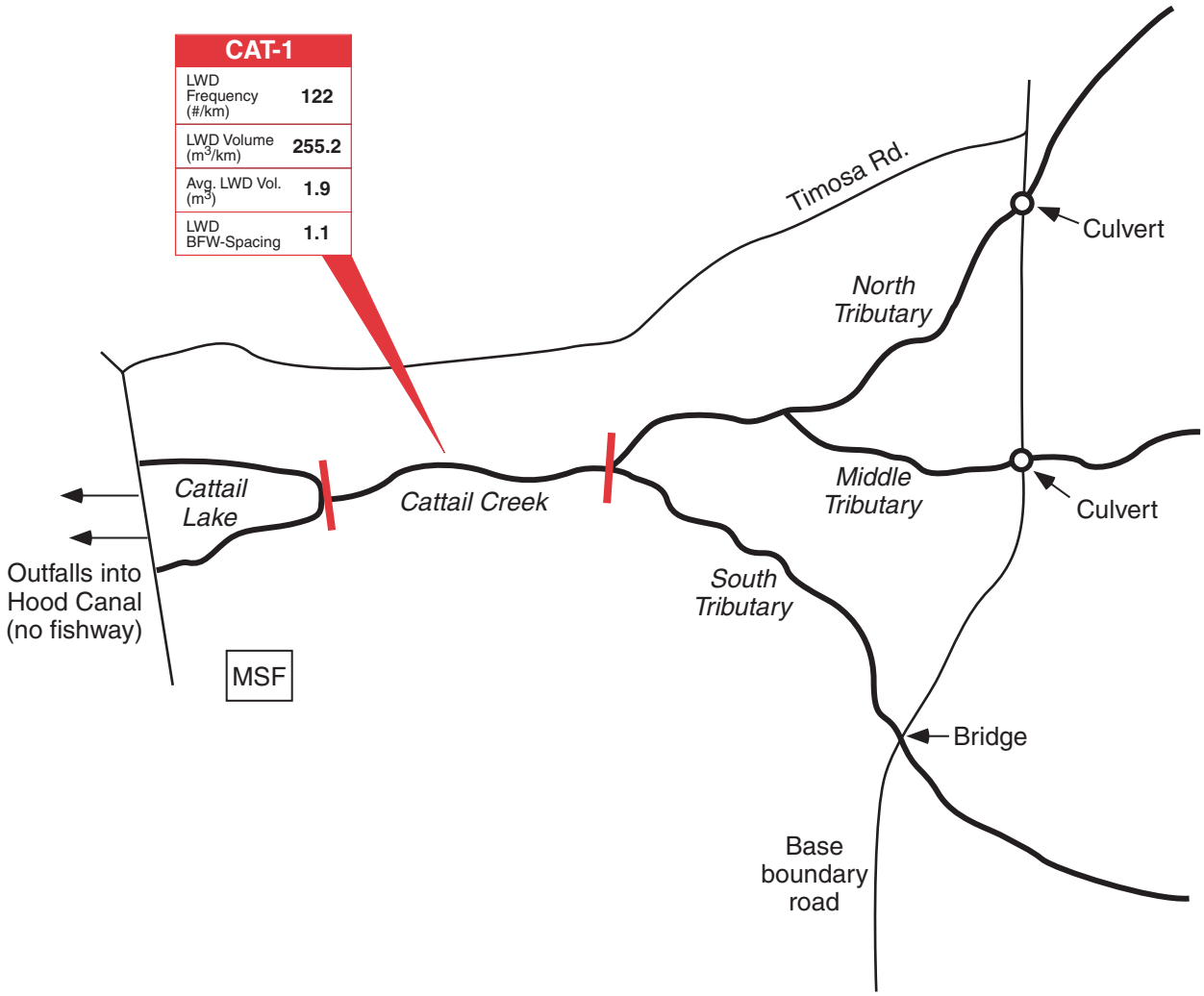
Naval Submarine Base (NSB) Bangor
Cattail Creek
Large Woody Debris (LWD) Survey Map



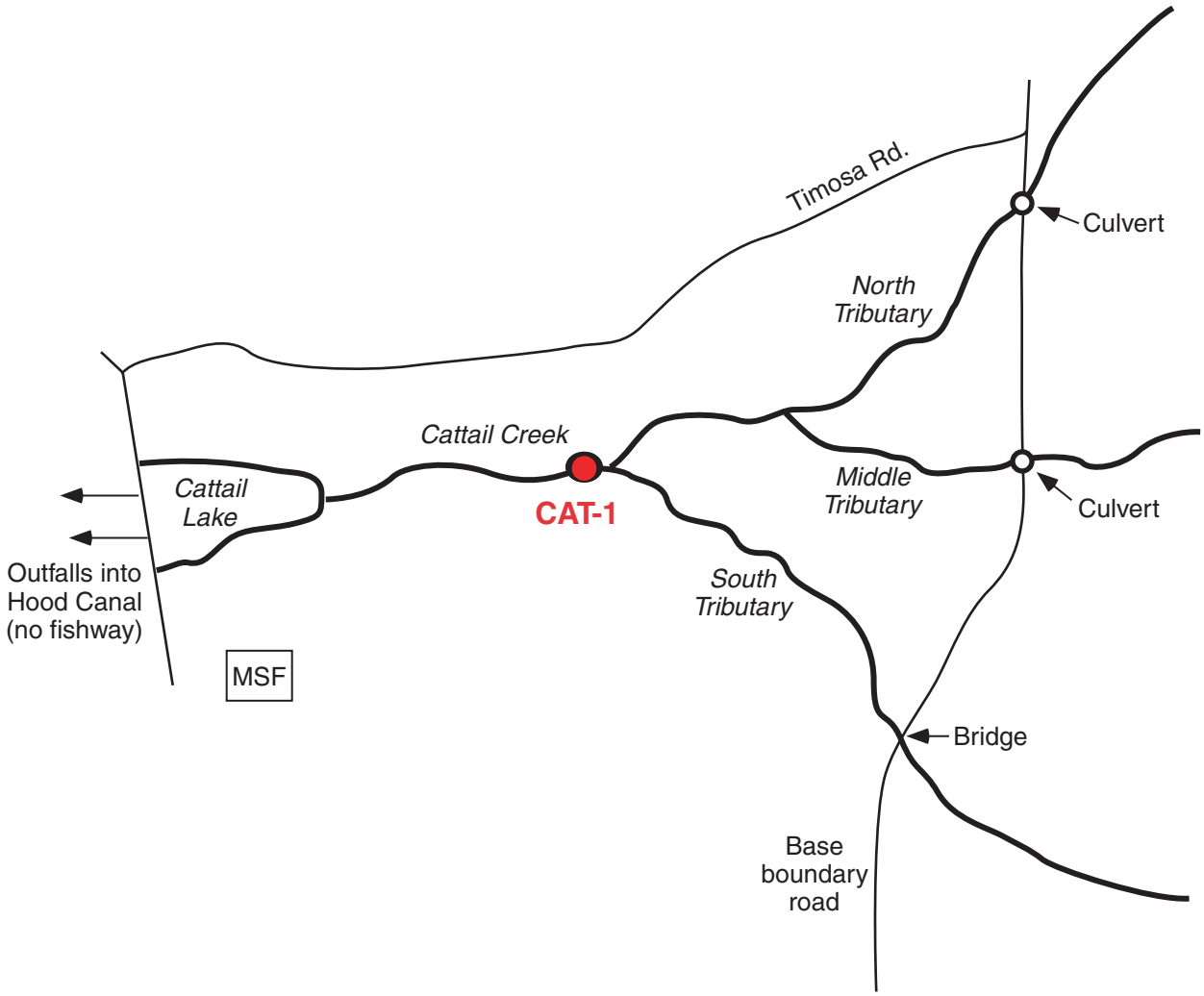
LEGEND

- Culvert
- Road
- Streams, lakes and wetlands
- Survey reach location (CAT-1)
- *See Map Legend J-9 for explanation*

(no scale)

N W E S

Naval Submarine Base (NSB) Bangor
Cattail Creek
Biological Monitoring Site Map

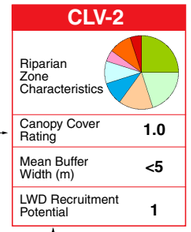


LEGEND

- Culvert
- Road
- Streams, lakes and wetlands
- Bio-monitoring site

(no scale)

RIPARIAN CONDITIONS LEGEND



Survey Reach Identification

Relative Percentages of Riparian Zone Characteristics:

- Mature Coniferous
- Young Coniferous
- Mature Deciduous
- Young Deciduous
- Mixed Mature
- Mixed Young
- Prairie
- Woody Shrubs
- Herbaceous Tall
- Herbaceous Short
- Landscaped
- Lawn/Turf
- Impervious

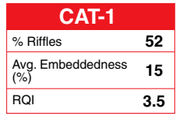
Canopy Cover Rating

80-100% Canopy Cover = 4
60-80% Canopy Cover = 3
40-60% Canopy Cover = 2
0-40% Canopy Cover = 1

LWD Recruitment Potential

Mature Coniferous Riparian w/adequate LWD = 4
Mixed Mature Riparian or w/o adequate LWD = 3
Mature Deciduous Riparian and/or w/o adequate LWD = 2
Lack of Riparian Forest & w/o adequate LWD = 1

SPAWNING HABITAT LEGEND



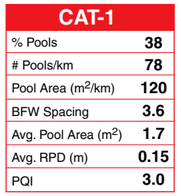
Survey Reach Identification

% Total Instream Habitat (Surface Area) in Riffles (40-60% is optimum)

Average Substrata Embeddedness (<10% is optimum)

Riffle Quality Index = Qualitative Rating of Spawning Habitat Quality (5 = excellent quality and 1 = poor quality)

REARING HABITAT LEGEND



Survey Reach Identification

% Total Instream Habitat (Surface Area) in Pools (40-60% is optimum)

Pool Frequency per km of Stream

Pool Area per km of Stream

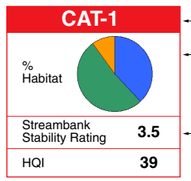
Bankfull-Width Spacings Between Pools (≤2 is optimum)

Average Area of Pools within Survey Reach

Average Residual Pool Depth

Pool Quality Index = A Qualitative Rating of Rearing Habitat Quality (5 = excellent quality and 1 = poor quality)

INSTREAM HABITAT CONDITIONS LEGEND



Survey Reach Identification

Relative Percentages of Instream Habitat Characteristics: % Pool % Riffle % Glide

Streambank Stability Rating

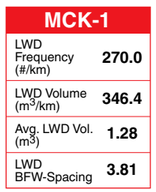
75-100% Stable/Vegetated = 4
50-75% Stable/Vegetated = 3
25-50% Stable/Vegetated = 2
0-25% Stable/Vegetated = 1

HQI Score

>40	Excellent	
30-40	Good	
20-30	Fair	
<20	Poor	

Shown along respective surveyed reach

LARGE WOODY DEBRIS (LWD) LEGEND



Survey Reach Identification

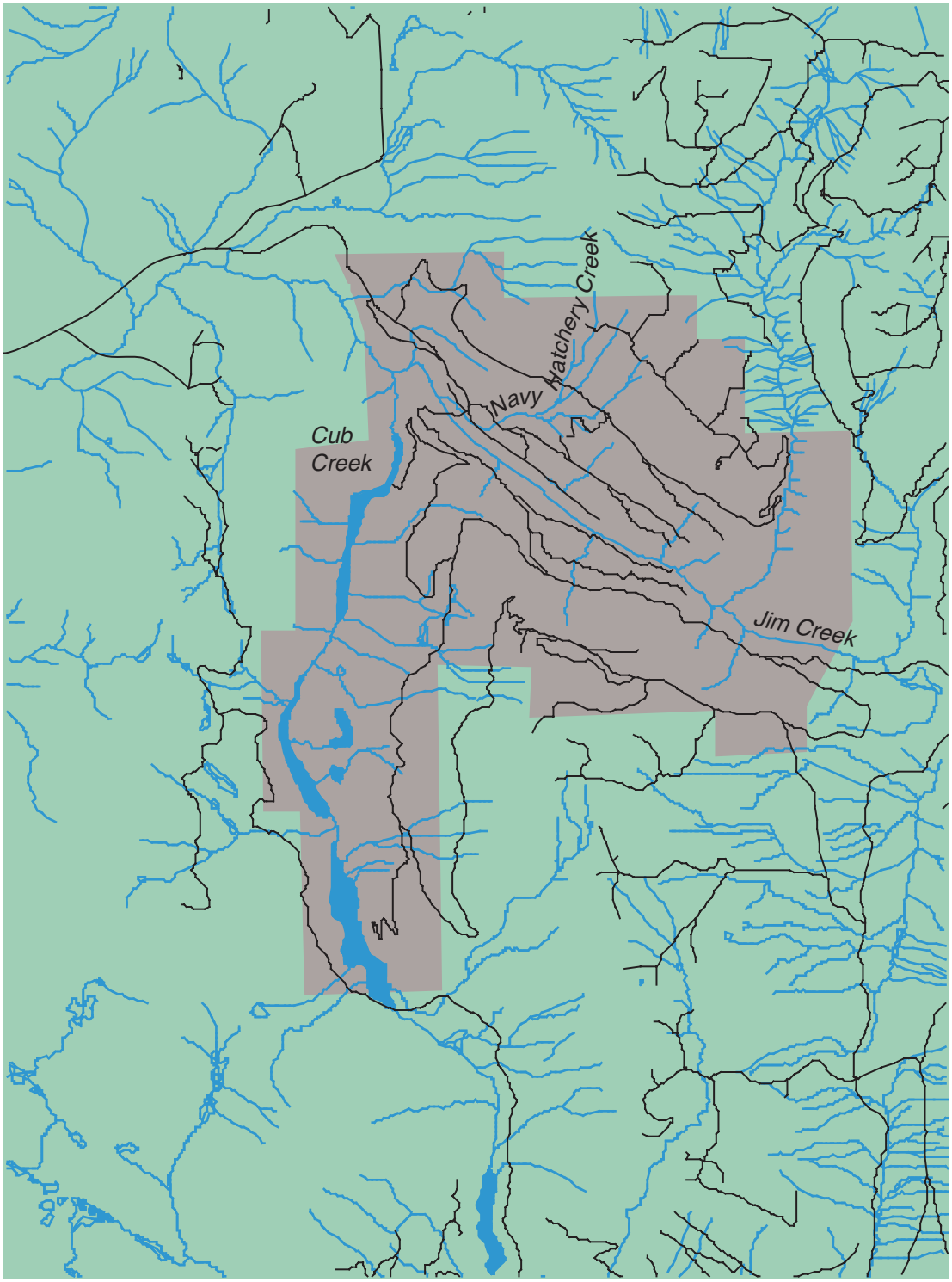
Frequency of LWD within Survey Reach

Volume of LWD within Survey Reach

Average Volume (size) of LWD within Survey Reach

Pieces of LWD per Bankfull-Width Spacing (≥2 is optimum)

Naval Communications Station
Jim Creek
Base Map



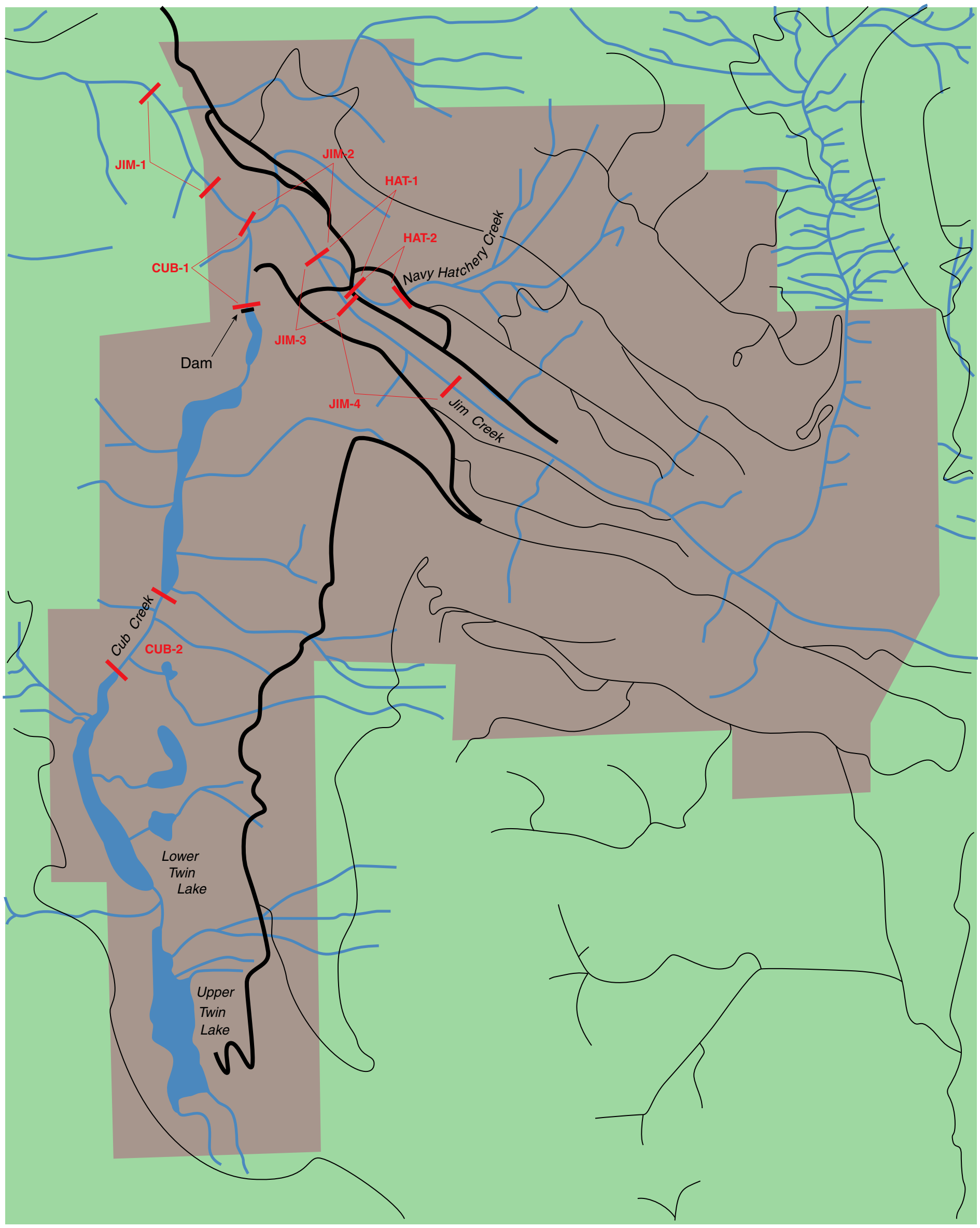
LEGEND

- Base
- Off Base
- Streams, lakes and wetlands
- Roads

N
W E
S

0 1 2 3
miles

Naval Communications Station
Jim Creek
Stream Survey Reach Map

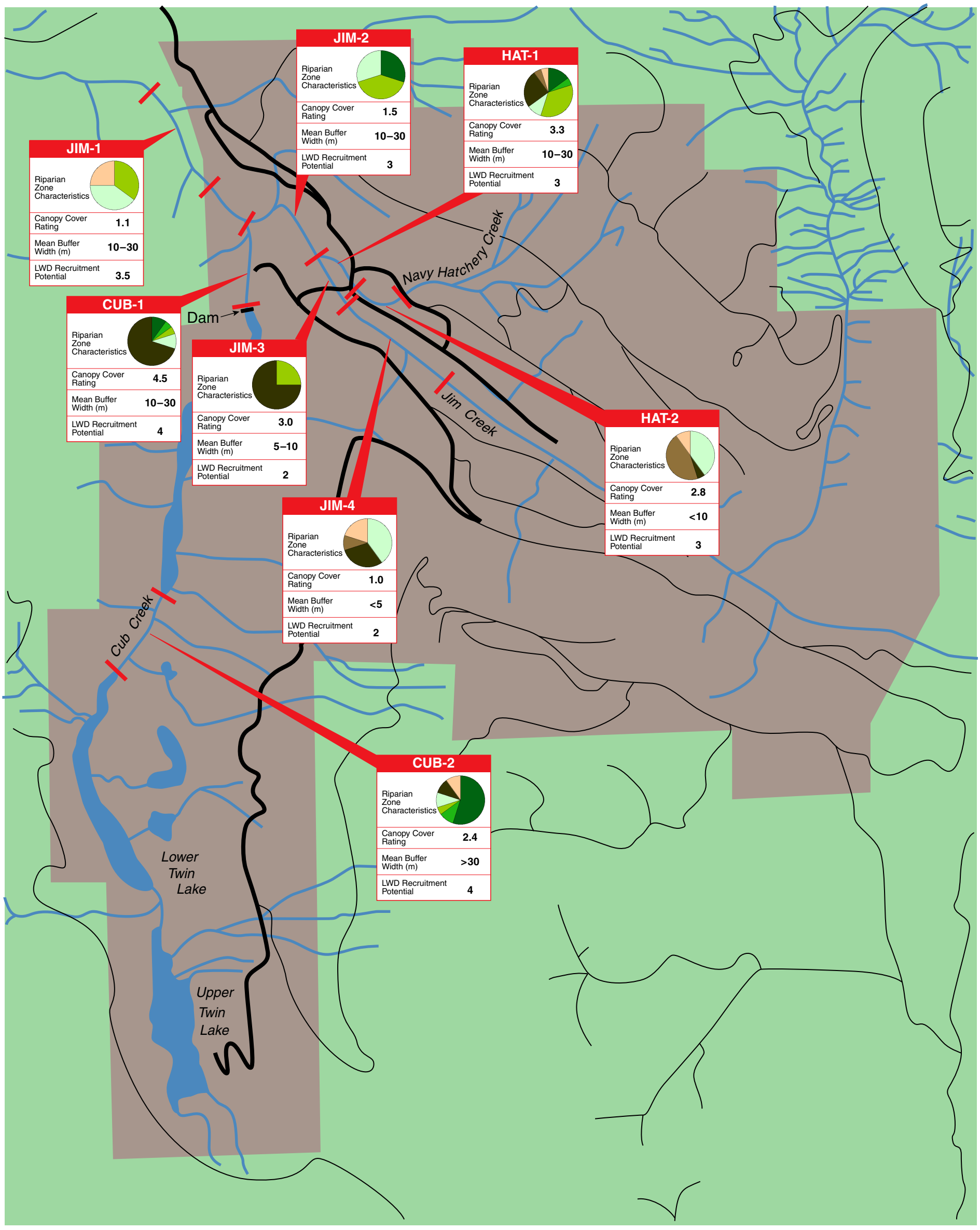


LEGEND

- Base
- Off Base
- Main Paved Roads
- Gravel Roads
- Streams, lakes and wetlands
- Survey reach location (CUB-1)

N W E S *(No Scale)*

Naval Communications Station
Jim Creek
Riparian Conditions Map

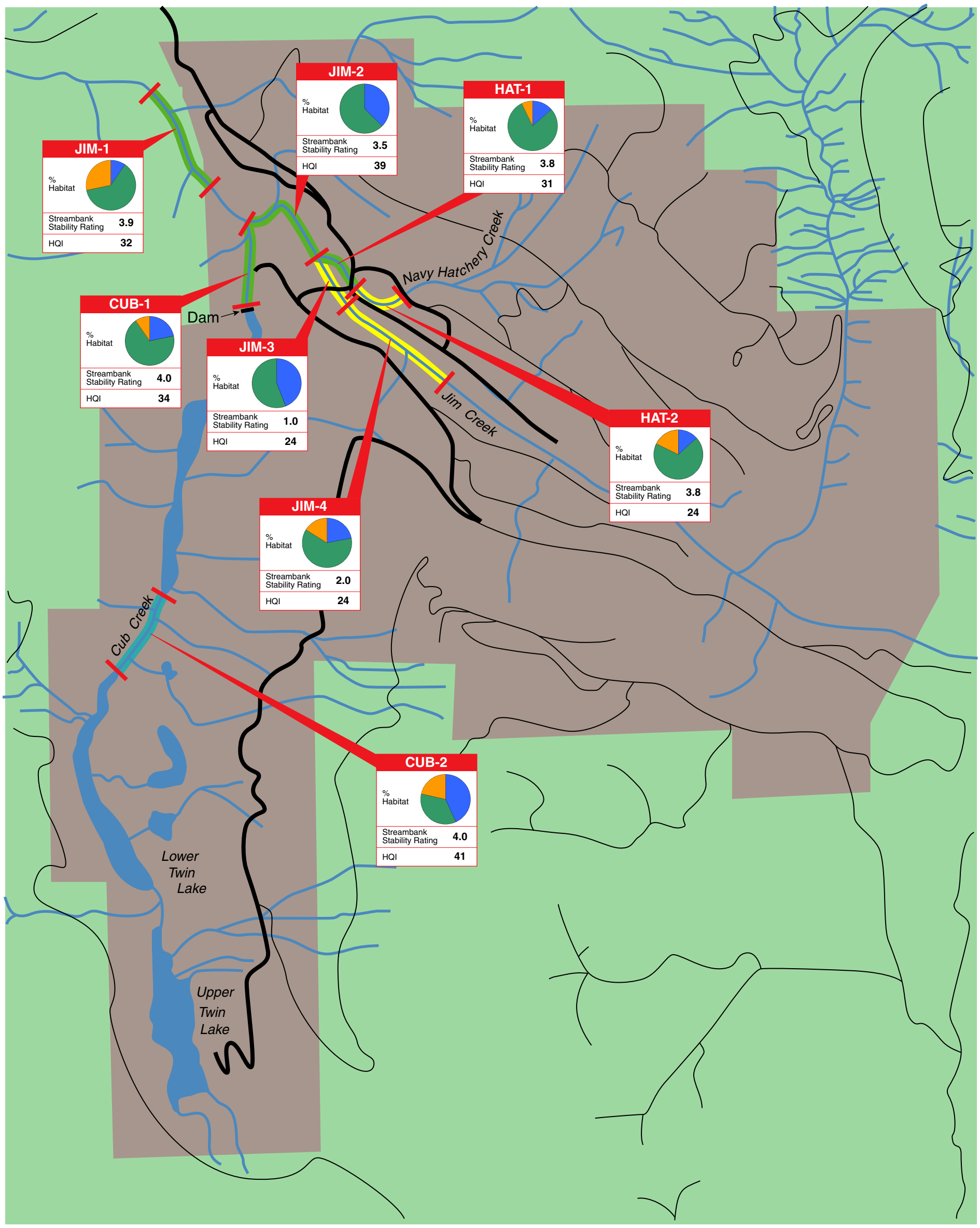


LEGEND

- Base
- Off Base
- Main Paved Roads
- Gravel Roads
- Streams, lakes and wetlands
- Survey reach location (CUB-1)
- *See Map Legend K-9 for explanation*

N W E S *(No Scale)*

Naval Communications Station
Jim Creek
Instream Habitat Assessment Map

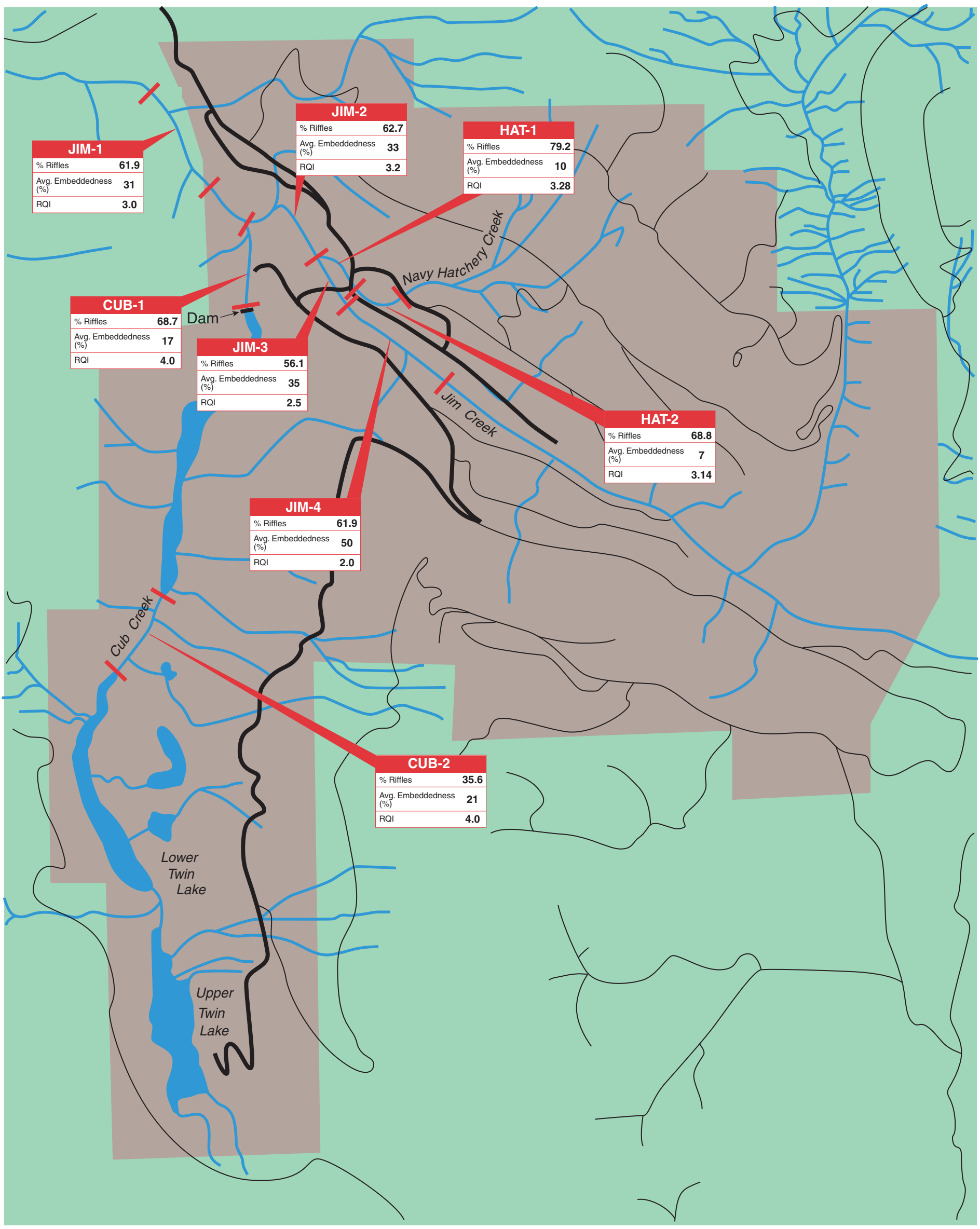


LEGEND

- Base
- Off Base
- Main Paved Roads
- Gravel Roads
- Streams, lakes and wetlands
- CUB-1 — Survey reach location
- JIM-1 — *See Map Legend K-9 for explanation*

N W E S *(No Scale)*

Naval Communications Station
Jim Creek
Spawning Habitat Assessment Map

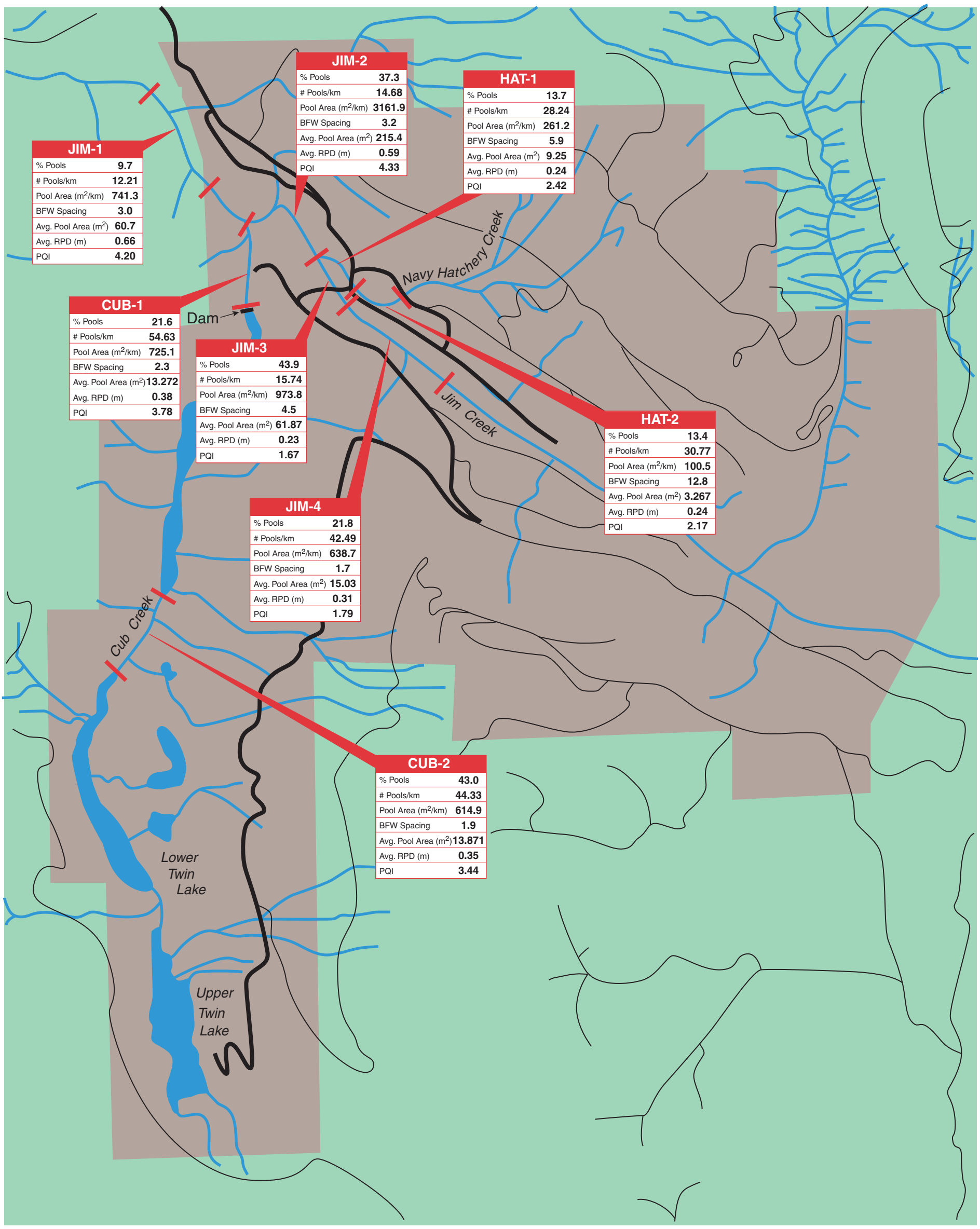


LEGEND

- Base
- Off Base
- Main Paved Roads
- Gravel Roads
- Streams, lakes and wetlands
- Survey reach location (CUB-1)
- *See Map Legend K-9 for explanation*

N W E S *(No Scale)*

Naval Communications Station
Jim Creek
Rearing Habitat Assessment Map



LEGEND

- Base
- Off Base
- Main Paved Roads
- Gravel Roads
- Streams, lakes and wetlands
- Survey reach location (CUB-1)

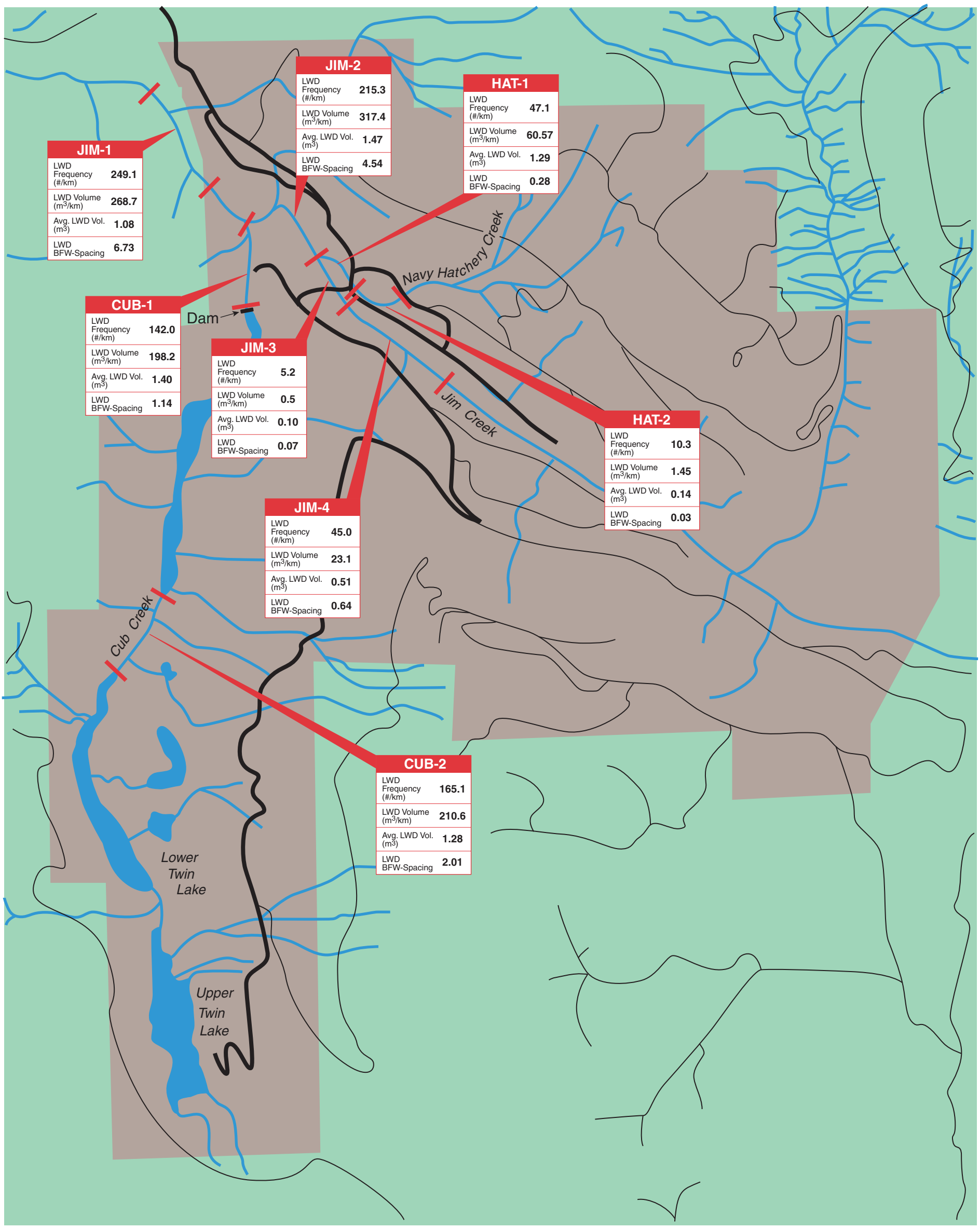
JIM-1
% Pools 9.7
# Pools/km 12.21
Pool Area (m2/km) 741.3
BFW Spacing 3.0
Avg. Pool Area (m2) 60.7
Avg. RPD (m) 0.66
PQI 4.20

See Map Legend K-9 for explanation

N W E S

(No Scale)

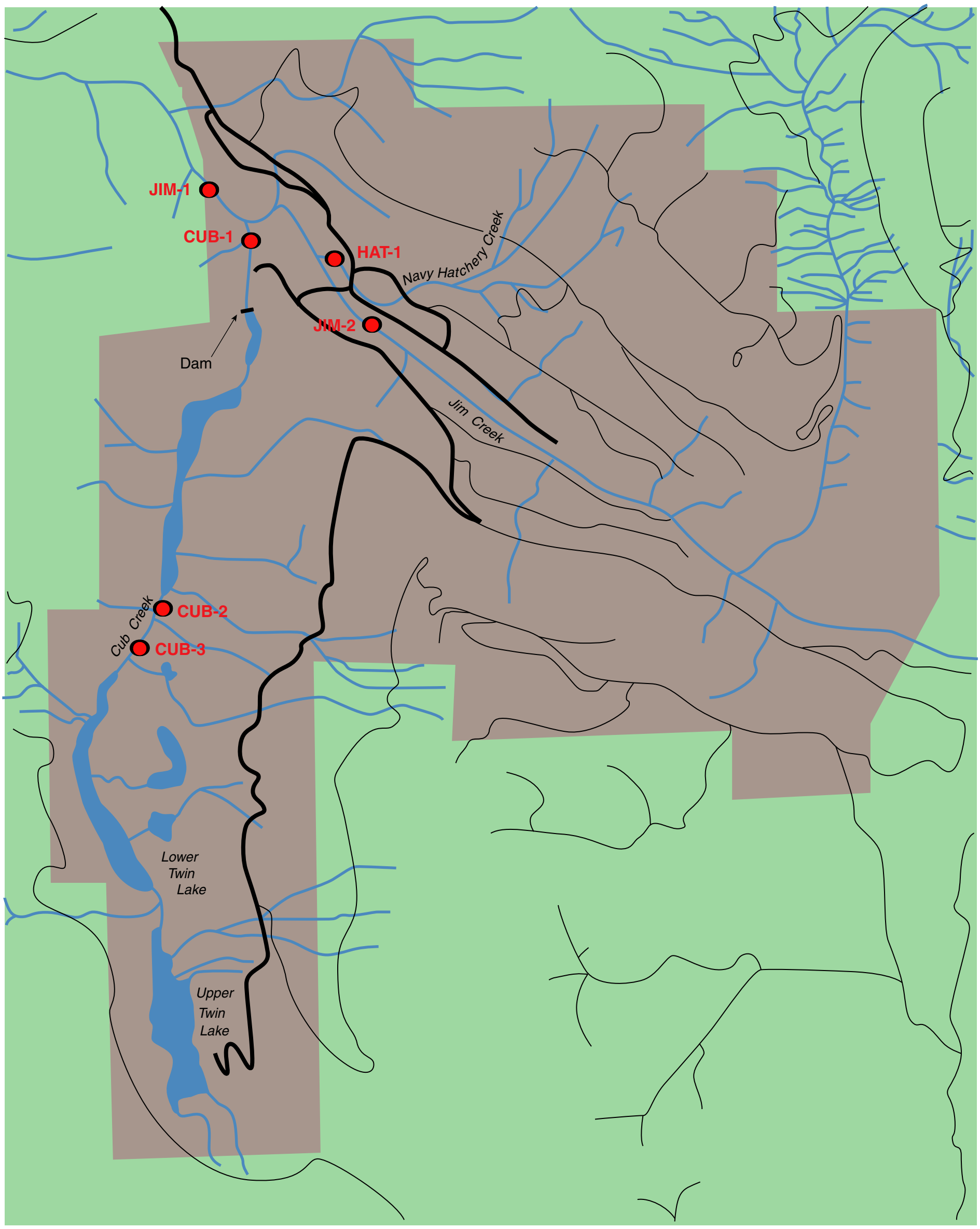
Naval Communications Station
Jim Creek
Large Woody Debris (LWD) Survey Map



LEGEND

- Base
- Off Base
- Main Paved Roads
- Gravel Roads
- Streams, lakes and wetlands
- Survey reach location (CUB-1)
- *See Map Legend K-9 for explanation*

Naval Communications Station
Jim Creek
Biological Monitoring Site Map

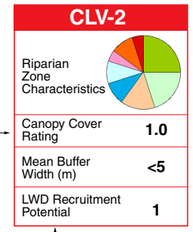


LEGEND

- Base
- Off Base
- Main Paved Roads
- Gravel Roads
- Streams, lakes and wetlands
- Bio-monitoring site

N W E S *(No Scale)*

RIPARIAN CONDITIONS LEGEND



Survey Reach Identification

Relative Percentages of Riparian Zone Characteristics:

- Mature Coniferous
- Young Coniferous
- Mature Deciduous
- Young Deciduous
- Mixed Mature
- Mixed Young
- Prairie
- Woody Shrubs
- Herbaceous Tall
- Herbaceous Short
- Landscaped
- Lawn/Turf
- Impervious

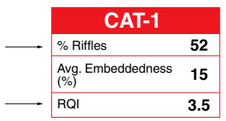
Canopy Cover Rating

80-100% Canopy Cover = 4
60-80% Canopy Cover = 3
40-60% Canopy Cover = 2
0-40% Canopy Cover = 1

LWD Recruitment Potential

Mature Coniferous Riparian w/adequate LWD = 4
Mixed Mature Riparian or w/o adequate LWD = 3
Mature Deciduous Riparian and/or w/o adequate LWD = 2
Lack of Riparian Forest & w/o adequate LWD = 1

SPAWNING HABITAT LEGEND



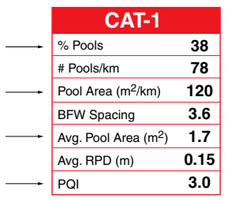
Survey Reach Identification

% Total Instream Habitat (Surface Area) in Riffles (40-60% is optimum)

Average Substrata Embeddedness (<10% is optimum)

Riffle Quality Index = Qualitative Rating of Spawning Habitat Quality (5 = excellent quality and 1 = poor quality)

REARING HABITAT LEGEND



Survey Reach Identification

% Total Instream Habitat (Surface Area) in Pools (40-60% is optimum)

Pool Frequency per km of Stream

Pool Area per km of Stream

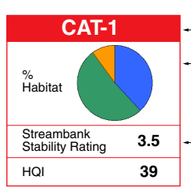
Bankfull-Width Spacings Between Pools (≤2 is optimum)

Average Area of Pools within Survey Reach

Average Residual Pool Depth

Pool Quality Index = A Qualitative Rating of Rearing Habitat Quality (5 = excellent quality and 1 = poor quality)

INSTREAM HABITAT CONDITIONS LEGEND



Survey Reach Identification

Relative Percentages of Instream Habitat Characteristics: % Pool % Riffle % Glide

Streambank Stability Rating

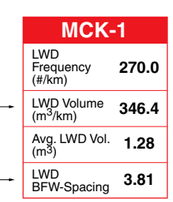
75-100% Stable/Vegetated = 4
50-75% Stable/Vegetated = 3
25-50% Stable/Vegetated = 2
0-25% Stable/Vegetated = 1

HQI Score

>40	Excellent	
30-40	Good	
20-30	Fair	
<20	Poor	

Shown along respective surveyed reach

LARGE WOODY DEBRIS (LWD) LEGEND



Survey Reach Identification

Frequency of LWD within Survey Reach

Volume of LWD within Survey Reach

Average Volume (size) of LWD within Survey Reach

Pieces of LWD per Bankfull-Width Spacing (≥2 is optimum)

Department of Defense Best Management Practices for Stormwater Run-off

Land-Use Type	Potential Stormwater Best Management Practices (BMP)
Roads, parking lots, sidewalks, and other paved surfaces	• Use low impact development (LID) technologies such as bioretention cells or biofiltration swales • Replace impervious pavement with permeable pavers or paving materials • Install sand filters—used to treat storm water runoff from impervious "hot-spot" areas • Eliminate curbs and gutters in favor of vegetated swales • Increase pervious areas—replace paved areas with pervious materials such as gravel
Construction and other ground-disturbing activities	• Erosion and sediment control (ESC)—stabilizing exposed soils prevents storm water run-on and runoff • Re-vegetate as soon as possible after construction is completed • Use geo-textile materials wherever appropriate to prevent erosion and sediment production • Use sedimentation basins to treat large sites • Cover excavated soils with mulch or compost • Remove contaminated soils and dispose of properly
NPDES permitted industrial point source (PS) discharges	• Prevent or reduce generation of pollutants • Improve personnel training; change processes to limit pollutants in effluent; research and use innovative or alternative treatment technology; improve sampling and inspection, enhance operation and management. • Require indirect dischargers to pre-treat wastes • Promotion of water conservation or reuse by consumers • Participate in basin-wide management plans that allow tradeoffs for maximum ecological and economic benefits (Chesapeake Bay program is an example of a "holistic" approach) • Involve community, schools, and other citizens in water quality sampling programs
NPDES non-point source (NPS) stormwater discharges	• Implement stormwater BMPs both structural and non-structural • Implement low-impact development (LID) approaches that combine hydrologically functional site designs with pollution prevention measures to reduce negative impacts on hydrology and water
Artillery or other live fire impact areas	• Spray mist across targets to knock down dust • Construct berms and basins to capture contaminated runoff • Use chemical coagulants and sealants to ensure runoff does not pollute ground water • Install a "bag-house" over targets to draw in contaminated air • Rotate training on grounds to minimize impacts on land

Training and maneuver areas	• Keep vegetative cover • Conduct scheduled maintenance of grounds • Rotate training areas to allow recovery • Utilize ESC practices to minimize runoff
Equipment or material storage sites	• Minimize materials stored on site • Reduce exposure—cover and store material according to permit • Implement community hazardous waste collection program—collect and remove substances from homes and tenants • Good housekeeping—clean site regularly and recycle empty drums and remove hazardous substances and wastes as soon as possible • Grade and reseed old stockpile areas and bare areas • Conduct preventive maintenance to reduce leaks, breakdowns, spills, and accidents (includes replacing worn seals, fittings, and other parts, and maintaining pollution control devices in good working order)
Fixed-wing and rotary-wing aircraft maintenance activities	• Minimize operational & maintenance (O&M) activities that occur outside in areas exposed to stormwater runoff • Use separate containers for disposal of wastes and recycle scrap metal • Dispose of degreasing and other solvent materials properly • Store containers on an impervious surface and properly cover against weather • Provide equipment training for O&M personnel
Open burning and ppen detonation (OBOD) Sites	• Review EPCRA TRI inventory requirements for toxic releases and disposal • Implement spill prevention, control, and countermeasures plan (SPCCP) • Utilize standard industrial classification codes for requirements regarding disposal of pollutants materials • Use separate containers for disposal of wastes • Store containers on an impervious surface and properly cover against weather • Collect downwind samples within the smoke plume as close to the burn event as possible considering access and safety limitations • Check fuel moisture requirements and weather criteria for “burn days” • Provide equipment training for O&M personnel

Ship building, maintenance and repair	• Use separate containers for disposal of wastes (many processes include potentially toxic, highly volatile, or flammable materials and should be clearly labeled and disposed of properly) • Recycle scrap metal • Properly dispose of degreasing and other solvent materials to avoid direct discharge into waste streams • Store containers on an impervious surface and properly cover against weather • Provide equipment training for O&M personnel
Motor pools and vehicle maintenance centers	• Park tank trucks or delivery vehicles away from unprotected storm drains or manholes, or provide temporary protection • Minimize operational & maintenance (O&M) activities that occur outside in areas exposed to stormwater runoff • Provide equipment training for O&M personnel • Properly dispose of degreasing and other solvent materials to avoid direct discharge into waste streams • Store containers on an impervious surface and properly cover against weather • Install sand filters—used to treat storm water runoff from impervious “hot-spot” areas
Fueling stations and operations	• Connect drains from vehicle washing areas to the municipal sewer or sanitary sewer system • Provide temporary protection of storm drains (temporary placement of absorbent material, storm drain covers, or shut-off valves) • Cover fueling area and isolate from stormwater runoff using deck drains or berms • Equip fueling equipment with automatic shutoff nozzles • Discourage topping off and unattended fueling • Install oil-water separators or sand filters—used to treat storm water runoff from impervious “hot-spot” areas
Fertilizer, pesticide, and herbicide application	• Institute an integrated pest management (IPM) program • Eliminate or decrease use—establish landscaping ordinances for business and industry to use native, hardy perennial species, which require less fertilizer and water than common landscape varieties • Revise landscaping contracts to require minimal fertilizer and pesticide application
De-icing material application	• Reduce use and/or replace with environmentally friendly materials • Collect and reuse materials • Provide temporary protection of storm drains (temporary placement of absorbent material, storm drain covers, or shut-off valves)

APPENDIX O. LOW IMPACT DEVELOPMENT BEST MANAGEMENT PRACTICES FACT SHEETS

Low Impact Development

Principles

Low Impact Development (LID) is an approach to site planning and design that has an objective of preserving watershed hydrologic functions while reducing construction and long-term maintenance costs for properties. This approach is quite different from conventional-end-of-pipe stormwater management. LID uses a combination of conservation practices and small-scale stormwater management (SWM) controls that are distributed evenly throughout the development to address stormwater SWM objectives. Several factors contribute to water quality degradation in a conventional development with a stormwater network based on conveyance and engineered BMPs. Large areas of imperviousness, including paved roads and parking lots, create and collect run-off as well as NPS pollutants. Developed sites are deforested, graded to remove natural depressional storage areas, and soil is removed or compacted. Engineered curb and gutter collection systems are designed to rapidly convey stormwater and provide little opportunity for infiltration and biofiltration. The effectiveness of conventional end-of-pipe treatment SWM is limited by site constraints and capacities.

LID is a relatively new concept in stormwater management, although its origins go back to the early days of stormwater management. This approach to SWM aims to preserve and restore the natural elements of the watershed hydrologic cycle. Infiltration is a key component of this SWM strategy, as is the treatment of stormwater using biofiltration and bioretention. LID also incorporates a site design strategy into new development, with a goal of maintaining or replicating the pre-development hydrologic regime through the use of design techniques to create a functionally equivalent hydrologic landscape. These hydrologic functions include depressional storage, soil absorption, infiltration, and groundwater recharge. In addition, the volume and timing of stormwater discharges to surface waters are maintained within the normal range through the combined use of structural and non-structural BMPs. Ideally, the quantity and rate of run-off (as well as infiltration and evapo-transpiration) leaving the site after development should be equivalent to the pre-development, natural conditions.

LID is based on the following five key principles:

- Conservation-based site design and planning
- Minimization of development impacts
- Maintaining natural watershed hydrology
- Integrated best management practices
- Pollution prevention planning and implementation

All of these concepts must be integrated into the design and be working together in order to achieve the design goal.

Conservation-based site design and planning

A major objective of the LID strategy is also the conservation of natural vegetation and the minimization of impervious surface area throughout the development. The protection of environmentally sensitive areas such as stream-riparian corridors, wetlands, steep slopes, floodplains, and nearshore areas is also an integral part of the LID strategy. Conservation-based site design and planning is based on preserving the natural features and character of the land and includes the following components:

- Forest conservation
- Wetlands preservation
- Wildlife habitat conservation
- Protection of stream-riparian corridors
- Protection of sensitive areas such as steep slopes
- Preservation of high infiltration soils
- Agriculture and open space preservation
- Preservation of culturally significant areas

Minimization of development impacts

A primary goal of LID is to minimize impacts to the drainage characteristics of the natural landscape during the development process. LID site design and stormwater principles also stress minimizing impervious surfaces and retention/restoration of natural vegetative cover, especially native forests and wetlands. Many construction impacts cannot be mitigated. Mitigation may also be extremely expensive and prohibitive in some cases, however, in most cases impacts can be minimized using simple LID-based measures. Some common techniques are:

- Minimize land clearing
- Phased land clearing
- Minimize mass grading
- Use alternative, permeable paving surfaces
- Reforestation of disturbed areas or planting new trees in open areas
- Disconnect impervious areas
- Reduce amount and size of the stormwater infrastructure (pipes, curbs and gutter)
- Consider alternatives to curb and gutter street designs
- Cluster development
- Narrow streets

- Sidewalks on one side only
- Roadside drainage in open infiltration swales
- Shared driveways
- Consider alternative parking lot designs

Maintaining natural watershed hydrology

In order to protect the integrity of the downstream channels, it is important to maintain, as much as possible, the natural hydrologic regime and the timing of run-off (time of concentration) from the site. The goal of LID is maintaining or replicating the pre-development hydrologic regime through the use of design techniques to create a functionally equivalent hydrologic landscape. These hydrologic functions include depressional storage, soil absorption, infiltration, and groundwater recharge. In addition, the volume and timing of stormwater discharges to surface waters are maintained within the normal range through the combined use of structural and non-structural BMPs. Ideally, the quantity and rate of run-off (as well as infiltration and evapo-transpiration) leaving the site after development should be equivalent to the pre-development, natural conditions. LID designs accomplish this by using the following site design and development techniques:

- Maintain natural drainage patterns
- Open drainage systems (swales and vegetated ditches)
- Flatten (low gradient) slopes
- Disperse drainage patterns
- Lengthen flow paths
- Save headwater areas from disturbance (especially wetlands)
- Increase setbacks from streams
- Utilize constructed wetlands for stormwater treatment where feasible

Integrated best management practices

Integrated BMPs consist of an array of site-scale stormwater retention and treatment techniques designed to fit into the developed landscape. This stormwater control strategy seeks to infiltrate run-off into the soil by allowing it to flow slowly (long flow paths with greater retention times) over permeable areas. These same areas can also be designed for other uses during non-storm periods (i.e., landscaped areas, wildlife habitat, or recreational areas). Based on the reduction in impervious areas and the increased infiltration goal, run-off volume is reduced significantly, and more water is available to maintain stream baseflows as well as recharge groundwater aquifers. In addition, the use of biofiltration and bioretention techniques can significantly improve run-off water quality.

LID principles are based on controlling (quantity) and treating (quality) stormwater at the source through the use of micro-scale techniques distributed throughout the development site. This multifunctional site design incorporates alternative SWM techniques and non-

structural BMPs such as functionally landscaped bioretention areas, biofiltration strips, vegetated drainage swales, infiltration trenches, and stormwater treatment wetlands. The LID approach can significantly reduce, or even eliminate, the need for centralized, engineered stormwater control measures. However, under some circumstances, both LID and conventional BMPs may be required to achieve SWM goals. The stormwater control/treatment techniques used in the LID approach offer an additional benefit in that they can be integrated into the site infrastructure, are generally more cost-effective, and are more aesthetically pleasing than conventional stormwater conveyance and control systems. The LID strategy also provides many opportunities to retrofit existing development, from suburban-level residential areas to highly impervious, urban environments.

Integrated BMPs are distributed on each lot for residential development or evenly throughout the site, as much as possible, on commercial and industrial projects to mimic the natural processes of storage, detention, infiltration, and evapo-transpiration. They are also located to strategically filter pollutants. Some common techniques include:

- Open drainage and infiltration swales
- Bioretention cells (rain gardens)
- Infiltration trenches and wells
- Biofiltration swales and filter-strips
- Pervious pavement or pavers
- Vegetated (green) rooftops
- Depression storage in grassed and parking areas
- Rooftop storage and rooftop rain gardens
- Rain water re-use (cisterns and rain barrels)
- Soil amendments (compost and organic matter)
- Soil rehabilitation (deep aeration and tilling)
- Sidewalk planters or tree boxes
- Extended-detention wetlands

Pollution Prevention

Reduction of pollutant loads at the source and an environmentally sensitive operation and maintenance plan are critical to the success of LID. The LID pollution prevention strategy includes initial notification of property owners about the requirements of maintaining LID sites and BMPs to ensure the long-term success and appearance of the development. An ongoing landowner education program, including educational pamphlets, operational and maintenance covenants, and involved homeowners associations are key components. Some common practices for landowners include:

- Integrated pest management
- Natural lawn care

- Hazardous waste management and disposal
- Recycling programs
- Good industrial/commercial housekeeping
- Industrial spill, prevention plans
- Manufacturers' safety data sheets
- Alternative, environmentally sensitive products

Utilize specialized structural BMPs (sand filters and drain-inlet inserts) for stormwater "hot-spots" such as vehicle fueling stations, vehicle maintenance areas, and industrial sites with a high potential for toxic pollution releases or spills

Low Impact Development
Commercial, Institutional, and Industrial Site Layout
Best Management Practices Fact Sheet

Objectives

Commercial, institutional, and industrial sites can provide numerous opportunities to reduce stormwater run-off and improve stormwater treatment through the use of LID features. In addition to the stormwater management (SWM) benefits, these landscape and site design modifications also have aesthetic benefits for owners and employees. These include on-site open space for passive recreation, energy savings, water re-use, supplemental irrigation water, and enhanced wildlife habitat. The exact suite of BMPs that are applicable to a specific site will depend on the site layout (site area, land-use type, street configuration, etc.) and characteristics (soils, gradient, forest area, etc.). These LID SWM techniques can be used for administrative offices (Figure 1), schools (Figure 2), retail centers (Figure 3), and light industrial complexes (Figure 4).

LID Techniques

LID principles are based on controlling (quantity) and treating (quality) stormwater at the source through the use of micro-scale techniques distributed throughout the development site. This multifunctional site design incorporates alternative SWM techniques and non-structural BMPs such as functionally landscaped bioretention areas, biofiltration strips, vegetated drainage swales, infiltration trenches, and stormwater treatment wetlands to name a few. The LID approach can significantly reduce, or even eliminate, the need for centralized, engineered stormwater control measures. However, under some circumstances, both LID and conventional BMPs may be required to achieve SWM goals. The stormwater control/treatment techniques used in the LID approach offer an additional benefit in that they can be integrated into the site infrastructure, are generally more cost-effective, and are more aesthetically pleasing than conventional stormwater conveyance and control systems. The LID strategy also provides many opportunities to retrofit existing development. The overall goal is to integrate stormwater management into a functional landscape and environmentally sensitive site design.

Integrated BMPs consist of an array of site-scale stormwater retention and treatment techniques designed to fit into the developed landscape. This stormwater control strategy seeks to infiltrate run-off into the soil by allowing it to flow slowly (long flow paths with greater retention times) over permeable areas. These same areas can also be designed for other uses during non-storm periods (i.e., landscaped areas, wildlife habitat, or recreational areas). Based on the reduction in impervious areas and the increased infiltration goal, run-off volume is reduced significantly, and more water is available to maintain stream baseflows as well as recharge groundwater aquifers. In addition, the use of biofiltration and bioretention techniques can significantly improve run-off water quality. The following LID BMPs can be used in these non-residential situations:

- Rooftop and driveway run-off disconnection
- Biofiltration swales and filter-strips

- Infiltration trench or basin
- Forest retention or buffer
- Bioretention cells or "rain gardens"
- Rain barrels or cisterns
- Permeable pavement or pavers
- Concave lawn area with infiltration basin
- Lawn and garden soil amendment
- Shared driveways

The specific suite of BMPs used for each site will depend on the unique characteristics of each site and the land-uses that currently do or will occupy the site. In most cases, the largest potential pollutant source will be vehicle parking areas (*Pitt et al*., 1995) These "source" areas usually represent the largest impervious areas within non-residential land-use areas. High-use parking lots, vehicle fueling stations, vehicle maintenance facilities, and industrial sites where toxic materials are handled or stored are the most common urban stormwater pollutant "hot-spots." These sites, especially industrial facilities may require the use of more conventional, structural BMPs for treatment of specific WQ problems. One of the most effective devices for treating these "ultra-urban" sites is the sand filter. These BMPs can be installed under parking lots or other paved surfaces (see Figure 4).

BMP Operations and Maintenance

Public education is critical for the long-term success of LID stormwater BMP operations. Users must understand the purpose of each BMP, how the individual BMPs fit into the overall site design, and how to optimize the performance of each BMP. In addition, basic maintenance must be clearly understood and carried out at the prescribed frequency. Most LID techniques are relatively simple and require no special operation and maintenance procedures. Periodic inspections of each BMP during storm events and under non-storm conditions will normally detect any problems. Grass used in biofiltration swales and vegetated filter strips must be maintained at a height of 6-8 inches. Infiltration devices and permeable surfaces must be protected from sediment/silt deposition that could potentially clog them. Rain barrels and cisterns should be cleaned periodically and kept covered so as not to a become a vector problem. All BMPs should be kept clean and free of litter or debris.

Reduction of pollutant loads at the source and an environmentally sensitive operation and maintenance plan are critical to the success of LID. The LID pollution prevention strategy includes user education about the requirements of maintaining LID sites and BMPs to ensure the long-term success and appearance of the development. An ongoing public outreach program, including educational pamphlets, operation and maintenance protocols, and involved employees are key components. Some common practices for commercial sites include:

- Integrated pest management

- Natural lawn care
- Hazardous waste management and disposal
- Recycling programs
- Good industrial/commercial "housekeeping"
- Industrial spill prevention plans
- Manufacturers' safety data sheets
- Alternative, environmentally sensitive products

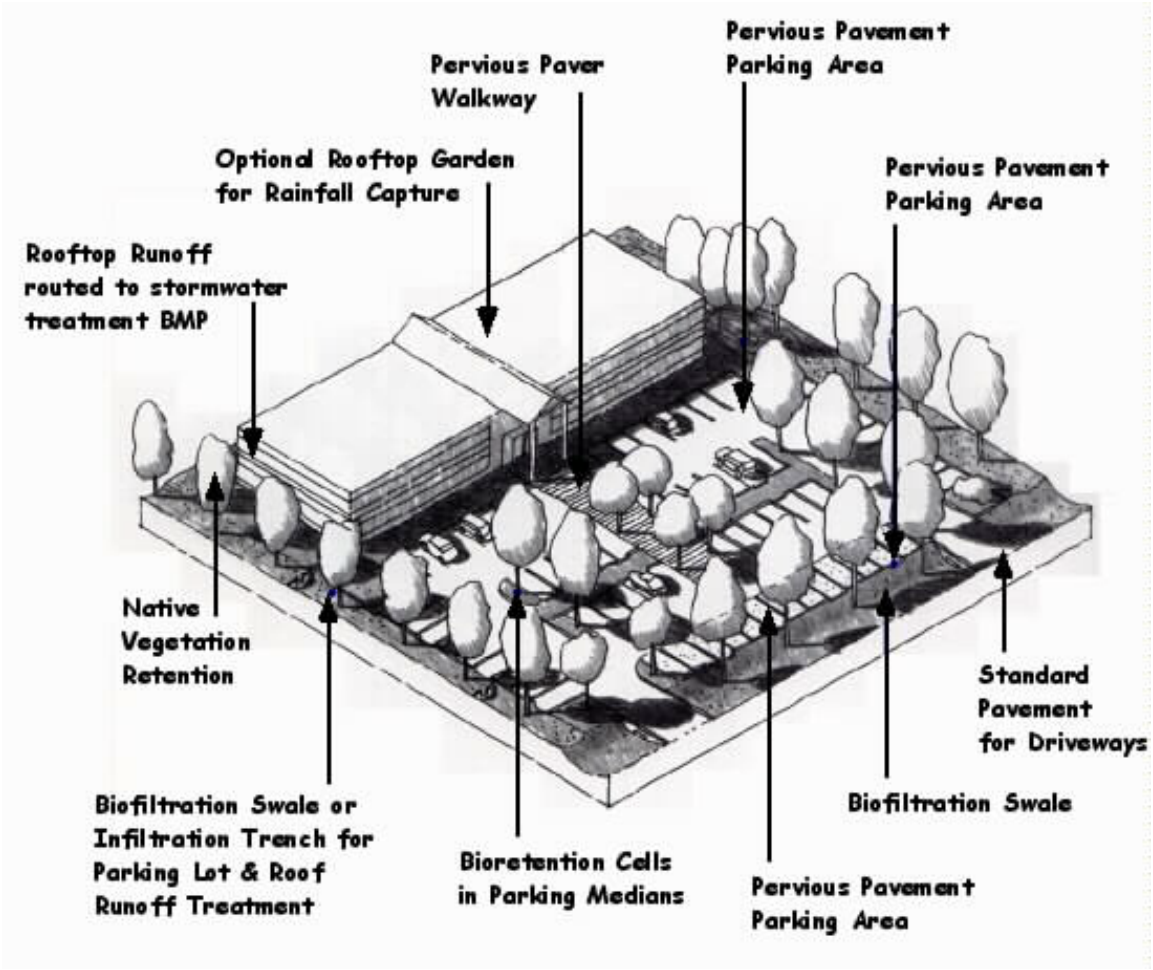


Figure 1. *Office or administrative building LID site layout, showing potential BMP applications (modified from* BASMAA, 1999*)*

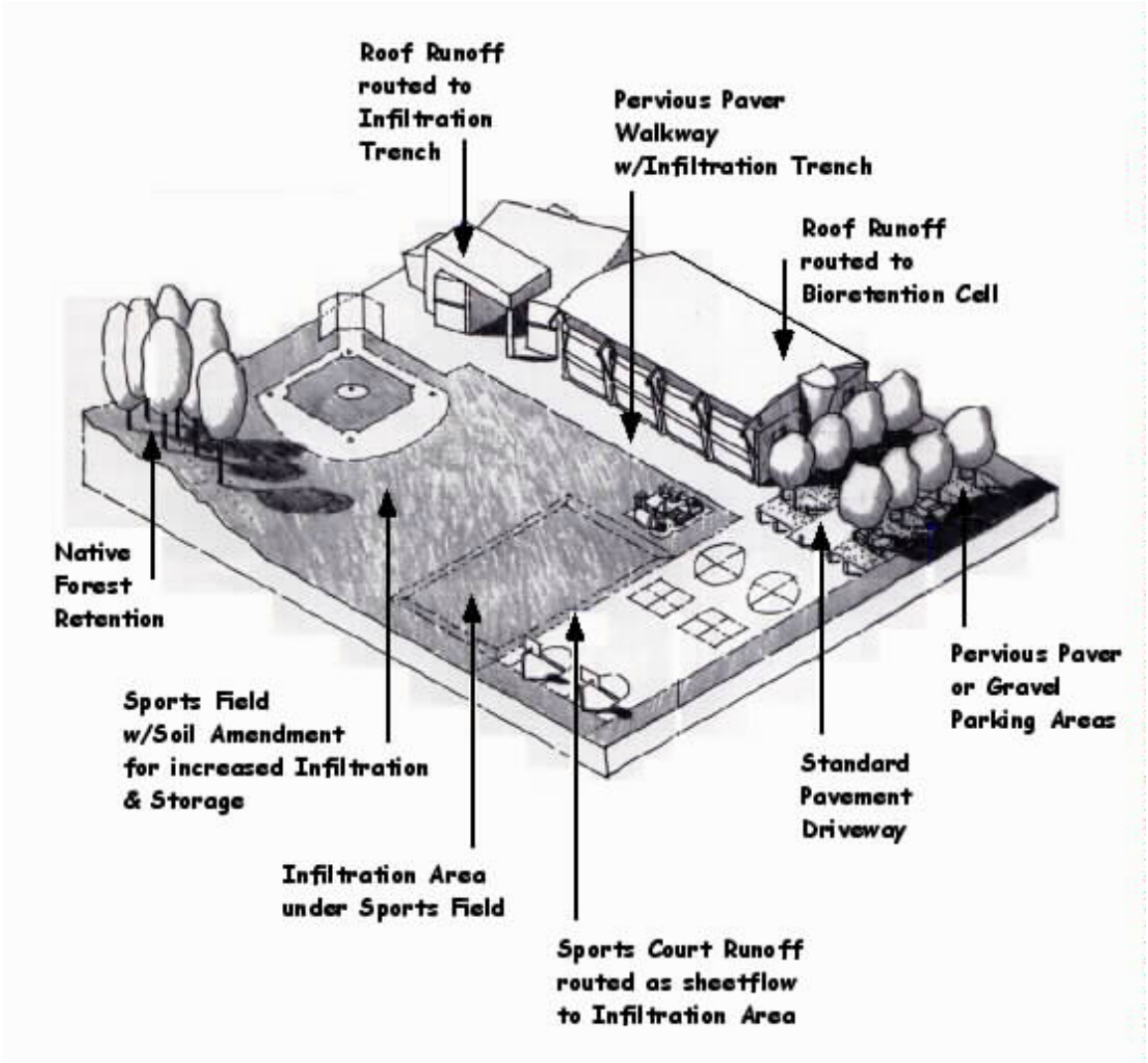


Figure 2. *School or campus LID site layout, showing potential BMP applications (*BASMAA*, 1999)*

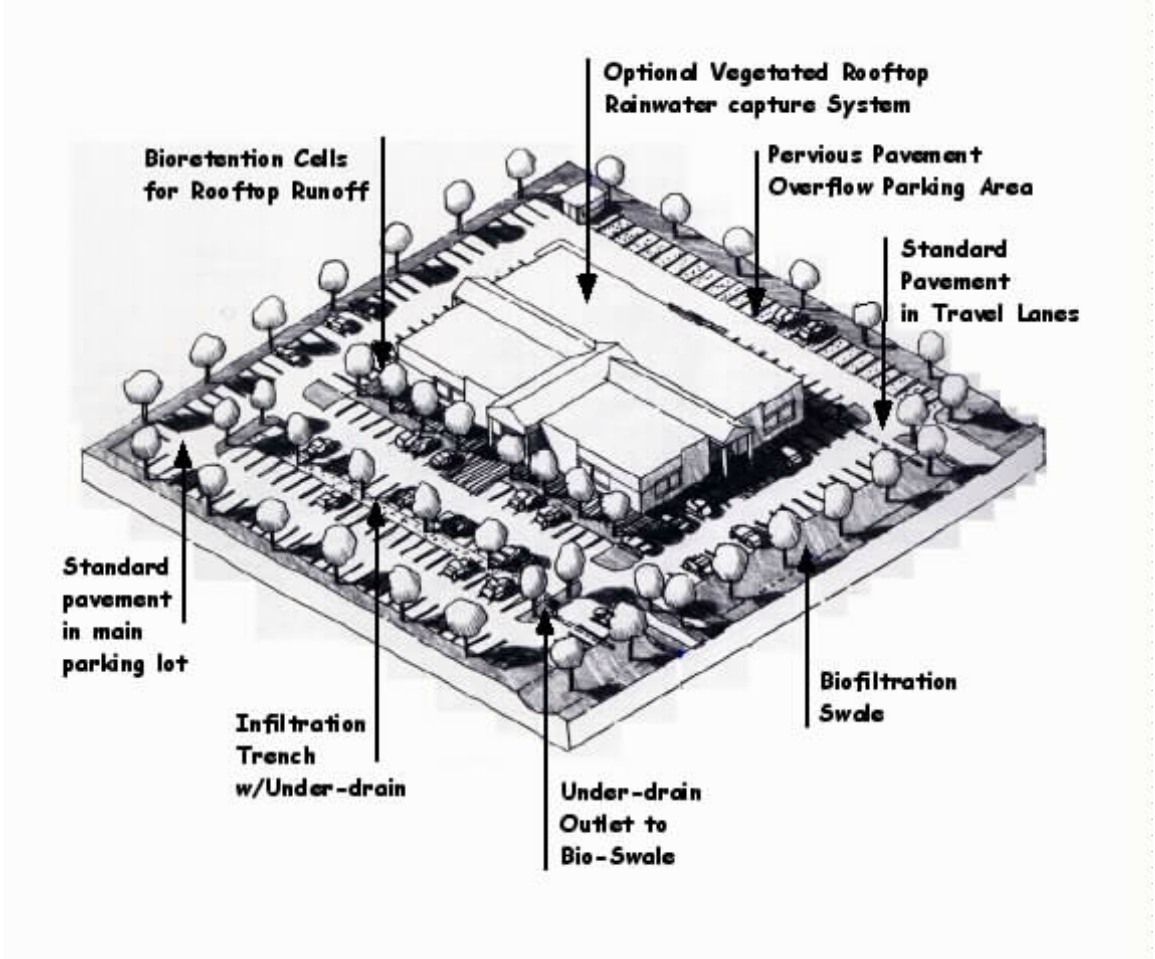


Figure 3. *Retail center LID site layout, showing potential (BMP) applications (*BASMAA*, 1999)*

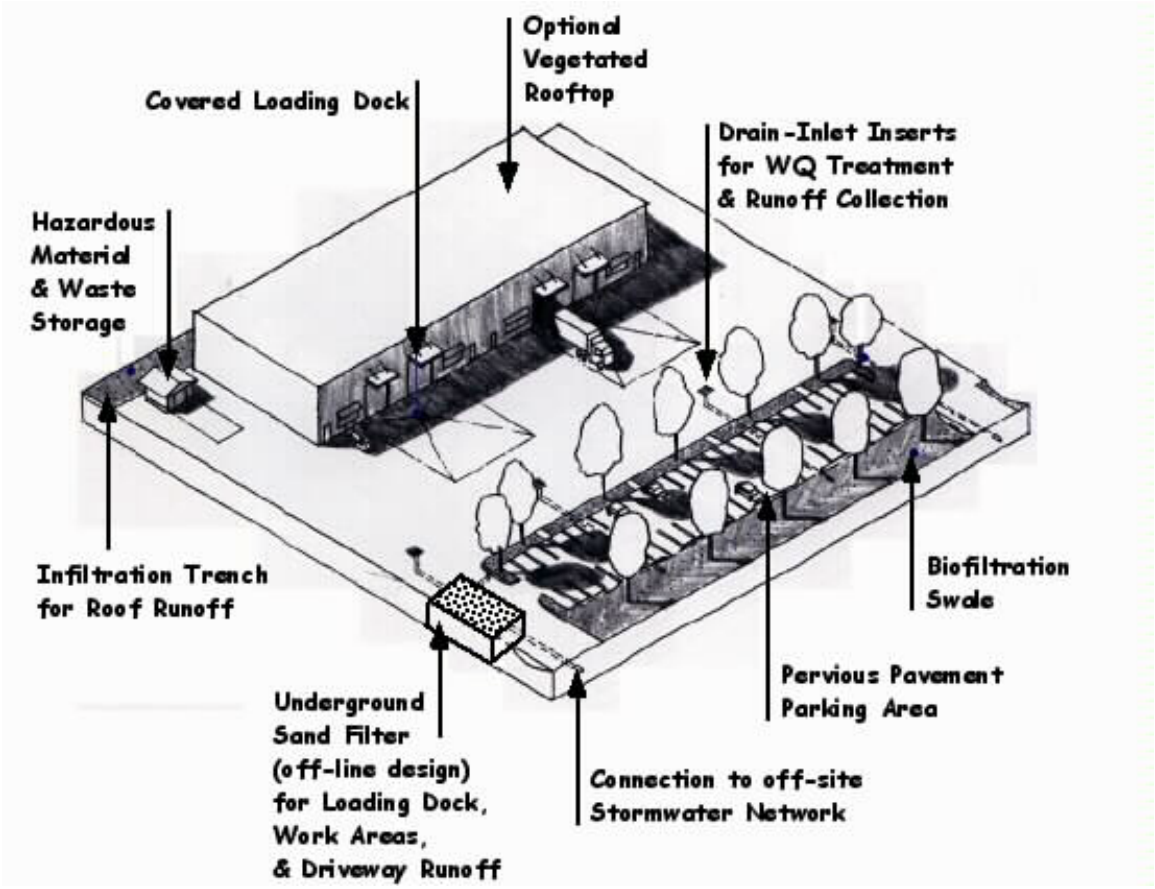


Figure 4. *Light industrial site LID site layout, showing potential BMP applications (*BASMAA*, 1999)*

Low Impact Development
Erosion and Sediment Control on DoD Installations
Best Management Practices Fact Sheet

Problem Description

Soil erosion and sediment production from military training areas, construction sites, borrow-pits, and open-burning and open-detonation (OBOD) sites is a significant water quality problem for the streams and rivers on Department of Defense (DoD) installations. The watersheds and aquatic ecosystems found on these bases are sensitive to the addition of fine sediment, excess nutrients, and non-point source (NPS) pollutants found in stormwater run-off. Human activities can accelerate the natural erosion processes by removing native vegetation, compacting or removing the upper soil horizon, changing natural drainage patterns by excavating or grading, and by covering soil with impervious surfaces such as concrete or asphalt (Figure 1). The cumulative effect of these impacts is that larger volumes of run-off are moving more rapidly across exposed soil areas, resulting in greater sediment loads being transported into receiving waters.

Objectives

The objective of this fact sheet is to provide a "toolbox" of best management practices (BMPs) for use by natural resource managers to protect and improve the water quality and ecological integrity of rivers and streams on DoD installations. This fact sheet focuses on surface erosion control from exposed areas such as construction sites, OBOD sites, or military vehicle training areas. A well designed and implemented erosion and sediment control (ESC) program forms the foundation of an integrated stormwater management (SWM) strategy. The US-EPA NPDES program requires ESC measures to be used on construction sites and for other activities that disturb the natural vegetation and soil structure.

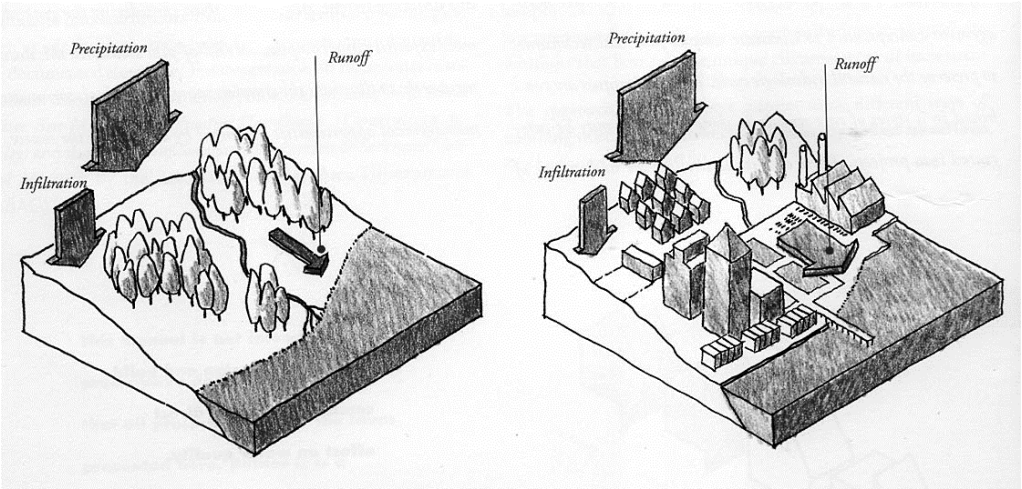


Figure 1. *Shift in the hydrologic cycle due to development*

Background

Construction Sites

The construction phase of the development is probably the most disruptive period in the entire development process. The combination of land clearing and grading has a major impact on the natural hydrologic regime of the sub-watershed in which the construction project is located. Even more significant is the landscape change and resultant hydrologic characteristics of the construction site itself. The loss of native vegetation due to land-clearing operations represents a significant loss of interception, evaporation, and transpiration of rainfall. In addition, grading operations almost always result in a loss of the upper soil horizon, which is typically the most absorbent layer. This can result in a loss of hydrologic storage capacity, a reduction in infiltration capability, and a major degradation in filtering for rainfall and run-off. Grading usually also results in a major alteration of local topography, which can result in a loss of natural depressional storage volume and a modification of the natural drainage patterns of the site. All of these impacts can result in significant changes in sub-basin hydrologic function and can have a dramatic impact on downstream aquatic resources.

Military Training Areas

Operational maneuver and training areas are unique landscape features found only on military installations. These are generally large, open areas, with little or no vegetation where military vehicles (tracked and wheeled) conduct realistic combat operations. Tracked vehicles (tanks and armored personnel carriers), for obvious reasons, can be very disruptive on the surface of the training area. In some cases exercises are conducted using explosive devices or ordnance. These types of operations are typically restricted to designated live-fire ranges. However, both types of military training activities can significantly disrupt the natural vegetation and surficial soil structure of the landscape. This tends to result in large-scale surface erosion and fine sediment transport. In many cases gully erosion or mass-wasting events can also result from these military training activities if proper ESC practices are not utilized. All of these impacts can result in significant changes in sub-basin hydrologic function and can have a dramatic impact on downstream aquatic resources.

Open-Burning and Open-Detonation Sites

OBOD sites represent another military-unique land-use activity. These sites consist of large open areas with little or no vegetation. Typical OBOD sites often have excavated trenches that are used for open burning of shell casings, propellant canisters, and other ordinance support materials. In addition, open-burning sites will have designated areas where expired or decertified propellant and gunpowder is burned in specially designed trays. Open detonation sites consist of bermed or excavated areas where explosives are destroyed via detonation. This operation involves burying the explosives to be destroyed in shallow pits and then remotely detonating them. This operation results in large surficial disturbances and the scattering of soil and explosive debris. In general, OBOD sites are being continuously disturbed and are extremely prone to surface erosion and sediment transport. Little or no source-control is possible at these sites for obvious reasons. All of these impacts can result in significant changes in sub-basin hydrologic function and can have a dramatic impact on downstream aquatic resources.

ESC Management

As regulatory requirements move towards more stringent NPS pollution controls, an effective ESC program becomes even more important as the first line of defense against water quality degradation. ESC BMPs also continue to evolve and improve as modifications are made, based on lessons learned, and as new technology comes into everyday operations. As is the case with stormwater management BMPs in general, not all ESC measures are the same. There is no one BMP that will work in every situation. To be effective, ESC measures must "fit" the site conditions. The key to success is in the planning phase. Site managers or project supervisors must perform a thorough site evaluation and carefully review the project plans before designing the ESC program for that particular site. The following questions should be asked.

- What type(s) of soil is present?
- What are the topographic conditions on the site?
- Are there special terrain features that must be considered?
- What is the drainage area of the site?
- How much of the site will need to be cleared?
- Can clearing and grubbing operations be done in phases?
- How much run-off will be generated on site?
- Is there off-site run-off that will need to be controlled?
- What are the anticipated peak flows?
- What storage/treatment capacity is required?
- Where does the water go after it leaves the site?
- Are there sensitive aquatic resources downstream?
- What are the discharge treatment goals?
- What is the ESC budget?
- How will ESC O&M be handled?

This information will assist the ESC manager in selecting the appropriate suite of BMPs to effectively deal with erosion and sediment control at the site. The most environmentally effective ESC measures also tend to be the most cost effective measures in the long run. This is due to the reduction in operation and maintenance requirements that go along with the optimum set of BMPs and the avoidance of fines and costly cleanup operations that often result from poor ESC practices (*Gannon*, 1999).

Principles of ESC

The foundation for a successful ESC program lies with the following basic principles. Most of these principles are normally associated with construction sites in the civilian world, but many of these principles can be applied to military training areas or OBOD sites, as well as construction sites within military installations.

1. Minimize the time that soil is exposed to rainfall and runoff. Clearing and grading operations should be done in phases, only clearing what is required for the work to be done at that time. In addition, clearing and grading should not be performed during the rainy season or when significant rainfall is predicted.
2. Minimize the area disturbed or cleared. Clear the site in phases so that only a minimum surface area is exposed to rainfall and runoff at any one time. Phased construction can be cost effective as well as environmentally responsible if planned well in advance and supported by the construction team.
3. Retain the maximum amount of natural vegetation possible on a site. Conservation of native vegetation, especially mature forest or wetlands, should be a major factor in designing the site layout. Preservation of natural vegetation on-site should be planned prior to the start of site disturbance activities. During construction, natural areas should be protected from disturbance. Avoid driving heavy equipment in the vicinity of large trees. The compaction of soils can damage roots and disrupt infiltration of rainfall. Rivers, streams, and wetlands should be isolated from construction sites by an appropriate natural buffer. Revegetation with native plants may also be a consideration if the site was previously cleared or developed. Natural vegetation has a significant advantage over post-disturbance "landscaping" in that it is adapted to local hydrologic conditions, provides natural pollutant filtration and nutrient uptake, supports native wildlife, enhances infiltration of rainfall, and provides aesthetic value to the site (Figure 2).

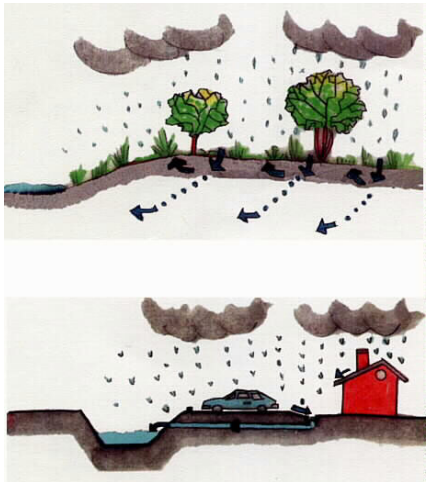


Figure 2. *Shift in natural hydrologic regime*

4. Stabilize disturbed or exposed soils as soon as possible. Temporary soil stabilization BMPs (straw-mulch, geo-textile material, etc.) can be installed immediately after clearing and grading. Permanent soil stabilization measures, such as native plantings or seeding should be as soon as possible after

construction is complete. Soil "stock-pile" areas should also be stabilized to prevent surface erosion and run-off. Roads used by construction vehicles or military vehicles should be stabilized to prevent surface erosion and dust production.

5. Prevent run-off from flowing across disturbed or exposed areas. Several ESC BMPs are available for this purpose. These include creating flow diversions or artificial channels to convey run-off into sedimentation ponds or sediment traps. Silt fencing, berms, and other diversion devices can be used to interrupt flows and divert run-off into vegetated areas as sheet-flow.

6. Slow down run-off flowing across or through sites. Energy dissipation BMPs should be used where necessary to reduce flow velocity on the site. These devices can be combined with flow diversion BMPs to slowly route runoff to sediment ponds or traps. In addition to "rip-rap" and other hard dissipation materials, vegetation also makes an excellent flow control and filtration media.

7. Provide dedicated drainage pathways for run-off flow control and water quality treatment. In general, vegetated or "rip-rap" swales work best. Utilize the natural terrain features where possible, but creation of berms and terracing may be necessary to route run-off to prevent erosion and to treat for sediment removal. Avoid the use of concrete channels or corrugated piping to convey run-off.

8. Treat stormwater run-off as close to the source as possible. In cases where source-control measures are ineffective or impractical, ESC BMPs should be utilized. These will be discussed in detail in the following sections. The overall goal should be to minimize sediment transport off-site. A site-specific combination of soil stabilization, flow control measures, and run-off treatment should be used to optimize ESC.

9. Permanent revegetation of disturbed areas should be accomplished as soon as possible after site-disturbing activities are complete. The use of native vegetation is encouraged, but climate and site conditions should dictate the appropriate plants and/or seeds for use in creating a long-term, cost-effective ESC solution that will require minimal maintenance support. Based on a review of current literature, it is strongly recommended that temporary irrigation be provided when establishing plantings for erosion control or for revegetation of disturbed areas. Plant mortality is very high during the initial year of growth and drops off significantly after that. In addition, native topsoil should be used as the primary planting media if available. If topsoil is unavailable, the inoculation of planting soils with mycorrhizal fungi is strongly recommended. In addition, soil amendments such as compost, should also be considered to improve plant establishment.

10. Riparian or streamside vegetation is an area of particular concern and its importance to aquatic ecosystems cannot be over-emphasized. These areas are often treated as "buffer zones" around wetlands and streams. These buffers are different than vegetated filter strips (VFS). Although each can be effective in reducing erosion and filtering sediment from run-off, natural riparian corridors should not be used as a primary means for ESC. These natural areas have significant ecological value and should be protected from disturbance, including

stormwater run-off and sediment inputs. The use of a VFS (grass and/or groundcover) is recommended to isolate the riparian area from the site of disturbance.

11. Streambank stabilization may be required for downstream receiving waters if disturbance activities within the watershed cause a shift in hydrologic regime. During post-disturbance inspections, downstream waters should be surveyed to assess the possible impacts of hydrologic change on the stream system. In many cases streambank stabilization will be required to repair damage or modify stream channels to prevent further damage (figure 3). The use of natural materials (vegetation, woody material, etc.) is preferred, however, the use of more structural materials such as "rip-rap" may be required in some cases.

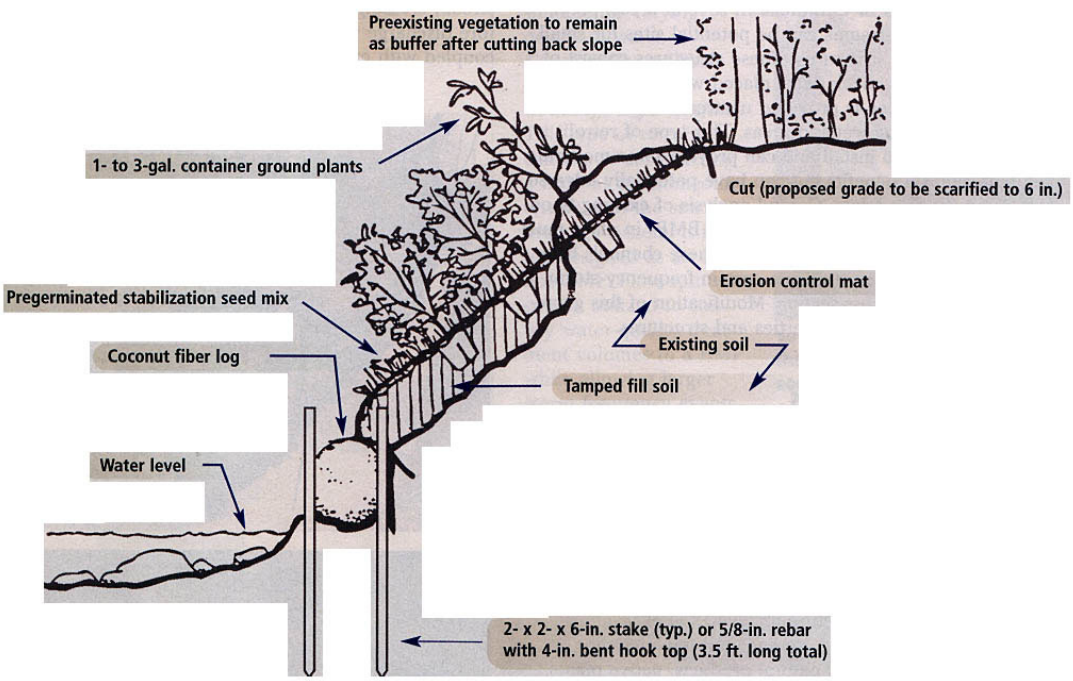


Figure 3. *Streambank stabilization*

ESC Best Management Practices

This section includes descriptions of standard ESC BMPs and their recommended applications. Numerous ESC products are available commercially. Each of these products should be evaluated for effectiveness prior to use on military installations.

Soil Stabilization Techniques

The use of mulch, rolled erosion control products or matting, and other materials for slope stabilization or soil erosion control is a common practice for construction sites. These BMPs may have application for military-unique disturbance sites (training areas, OBOD sites, etc.) as well. Table 1 provides a summary of soil stabilization BMPs.

Biodegradable mulch soil stabilizers (BMSS) are often used as a temporary erosion control measure in areas where seeding cannot be used because of time constraints or lack of irrigation water. Mulch cover can provide quick, inexpensive, and relatively effective ESC. Mulch alone is not recommended for slopes greater than 2:1 or for areas prone to heavy surface run-off flows. Mulch should be used in conjunction with hydro-seeding on slopes greater than 2:1. Straw is the most common mulch. It is generally an excellent ESC material and tends to be readily available (Table 1). Straw mulch is an effective temporary ESC measure for approximately 3-6 months, depending on local climate conditions. Straw fibers effectively absorb raindrop impact, reduce runoff, promote infiltration, moderate soil temperatures, conserve moisture, trap soil particles, and promote vegetation establishment. In addition, the inter-weaving characteristic of straw mulch provides effective water and wind erosion protection. Potential drawbacks to the use of straw mulch include fire hazard and weed germination.

Prior to mulching the site may need to be modified for surface run-off control. The use of swales, terraces, berms, and level-spreaders are typical of these measures. Straw mulch can be applied by hand or by blower. Anchoring of the mulch is critical to the success of this ESC technique. Common anchoring methods include crimping, disking, rolling or punching. Netting can also be used to hold mulch in place. The use of chemical binders or "tacifiers" is also becoming common. Any of these chemical products used should be environmentally sensitive and biodegradable. Mulched surfaces may require periodic maintenance to re-anchor areas, or reapply mulch/tacifier in spots where it has eroded.

Compost and wood fiber mulch have also been used successfully as a soil stabilization material (Table 1). Straw mulch combined with an erosion-control seed mixture and composted manure or fertilizer is also an effective method, especially on steep slopes. The combination of mulch and seeding is probably the most effective soil stabilization technique for both short and long-term ESC in most situations. The use of fertilizers and manure should be avoided where downstream waters are nutrient impaired or sensitive to nutrient addition. Recycled paper mulch and chemically-bound (tacifier) fiber-matrix mulches are also available commercially (Table 1). The typical application density for mulch is between 2 and 4 tons per acre. Cost estimates for these ESC techniques (including installation and routine maintenance), on a per-hectare basis, for about 6 months of coverage are shown in Table 1.

Rolled erosion control products (RECP), commonly referred to as matting or erosion-control blankets are the second major category of temporary soil stabilization materials. The use of matting is another common ESC technique that is especially effective on steep slopes or in areas prone to erosive run-off flows. RECP typically come in rolls that are spread out on the ground and held in place using stakes, wire staples, geo-pins, or other fastener systems. These ESC materials are often used to stabilize steep slopes or drainage channels. In most cases, RECP are applied in combination with vegetation for combined short and long-term ESC. Many of the RECP listed here can be obtained with an erosion-control seed mixture impregnated into the mulch-matrix, or in some cases, sod can be grown as an integral part of the rolled mesh-mulch matrix. In any case, the vegetation used in conjunction with the RECP (hydro-seeding, seed, sod, or plantings) must be appropriate for the local site conditions (soil moisture, climate, nutrients, etc.). Chemical tacifiers may also be incorporated into RECP materials. If not properly installed, matting

can allow water to flow underneath. This could result in surface erosion or even gully formation if not corrected. For this reason, it is a good practice on slopes to start laying the matting at least 1 meter over the crest of the slope and at least 1 meter beyond the toe of the slope. When using RECP in channels or ditches, unroll the matting in the direction of water flow. The use of a level-spreader device to encourage sheet-flow and energy dissipating material is also recommended. In addition, do not place the seam between adjacent rolls at the base of the channel, but instead off-set it from the axis of maximum flow energy and ensure that it is secured well to the underlying ground.

There are a number of matting materials available on the commercial market, with jute mesh, woven straw, coconut fiber (coir), or wood-fiber (excelsior) being the most common biodegradable products. Biodegradable RECP are composed of a mulch material held in a matrix of biodegradable mesh or netting. Most of the biodegradable RECP materials have a useful life of about one year. This is typically long enough for permanent vegetation to become established as the primary erosion control measure. Most of the biodegradable mesh-matting allows light to pass through for plant growth, helps retain soil moisture, and decomposes in 2–3 years. Biodegradable RECP matting is not recommended for slopes greater than 2:1. The relatively high cost (Table 2) of some of these RECP materials makes them suitable only for small or very problematic sites.

There are also several non-biodegradable products on the market for ESC. The material and/or the matrix may be non-biodegradable, depending on the product. These include plastic netting or mesh, plastic sheeting, woven geo-textile material, plastic geo-grids, bonded synthetic fiber mesh or sheeting, and combination synthetic and biodegradable blends. Table 2 summarizes the pros and cons of the most common RECP materials. Most of the non-biodegradable materials (especially the plastics) are photo-degradable, but may still leave residual material in the soil even after several years. Plastic sheeting and woven geo-textile sheeting is impervious to rainfall or stormwater infiltration. This may be a desirable characteristic in some cases (e.g., near-vertical slopes that will be stabilized with retaining walls at the end of the construction phase), but may be unsuitable in other situations where infiltration is desired or vegetation is being established. The relatively high cost (Table 2) of some of these RECP materials makes them suitable only for small or very problematic sites. A relatively new RECP now on the market is commonly referred to as turf reinforced matting (TRM). These products are available in several forms from different manufactures. All use a combination of geo-textile material, biodegradable matting, and turf (grass seed/sod). These RECPs are designed to be semi-permanent or permanent installations and appear to work very well.

<u>Hydraulically applied soil stabilizers (HASS) are the third group of soil stabilization BMPs</u>. This family of ESC techniques or products include hydro-seeding, plant-based and petroleum-based emulsions, gypsum, and polymeric emulsion blends (PEB). Table 3 provides a summary of HASS materials and their ESC characteristics. Most of these products are hydrocolloids or muciloids that are applied using hydro-seed equipment. After drying, they form a re-wettable membrane that binds soil particles together, but also allows seed to germinate and grow through the surface. Some are made from plant-derived material and some are petroleum-based. Gypsum is probably the oldest HASS product in this family of soil stabilizers. The recent CalTrans ESC study found gypsum to be the least effective product on the market. The newest group of HASS products is the

polymeric emulsion soil stabilizers (acrylic co-polymer hydrocolloids). These products have shown great promise in recent ESC applications in the Pacific Northwest (*Tobiason et al*., 2001). These tests, conducted by the Washington State Department of Transportation (WSDOT) found that soils treated with polyacrylamide (PAM) mixed with hydro-mulch and seed, resulted in a 90-99% reduction in downstream turbidity. The use of PAM and similar HASS products is strongly recommended, especially for disturbed areas and erosive slopes within watersheds of sensitive waters.

Physical slope treatment techniques are often used to prepare disturbed areas for revegetation and/or to prepare slopes for installation of BMSS or RECP materials. In general, surface roughening is considered a temporary ESC practice. These techniques usually involve the use of tracked construction vehicles to stabilize disturbed soils on slopes no steeper than 2:1. The soil surface is roughened or scarified by forming grooves, depressions, or steps that run parallel to the contour of the landscape. Soils that are cohesive and not fine-grained may be left in this condition for short periods without concern for major erosion. It is recommended that an additional soil stabilization measure be applied to provide optimum ESC (i.e., BMSS, RECP, and/or HASS). Surface roughening dissipates flow energy, reduces runoff velocity, increases infiltration, and traps sediment. Surface roughening also enhances the establishment of vegetation and can improve the performance of RECP or BMSS if used in concert with those BMPs.

In general, surface roughening is appropriate for almost all slopes, although the specific technique depends on the local soil, climate, and topographic conditions. A recent study conducted by the California Department of Transportation (*CalTrans*, 2000) evaluated several of the most common slope roughening techniques under controlled laboratory conditions (Table 4). These tests found that using specialized attachments for tracked vehicles, designed specifically for ESC, can significantly improve the performance of roughened slopes with regard to erosion control.

Slopes steeper than 2:1 should be stair-step graded. Cut slopes between 3:1 and 2:1 can be grooved or stair-step graded. Fill slopes between 3:1 and 2:1 should be grooved. Slopes less than 3:1 can be track-walked if necessary, but in most cases simply scarifying the surface will be adequate prior to seeding and mulching. It is important to avoid excessive compacting of the soil surface during roughening operations, especially when heavy equipment is being used. Soil compaction can reduce infiltration and inhibit plant growth. In most cases, as a minimum, roughened surfaces should be seeded with a locally approved erosion-control seed mixture. Periodic inspections are required for roughened slopes, especially after large storm events, to check for rill or gully erosion. Table 4 summarizes the various roughening techniques and Figures 4a-4e also illustrate each technique.

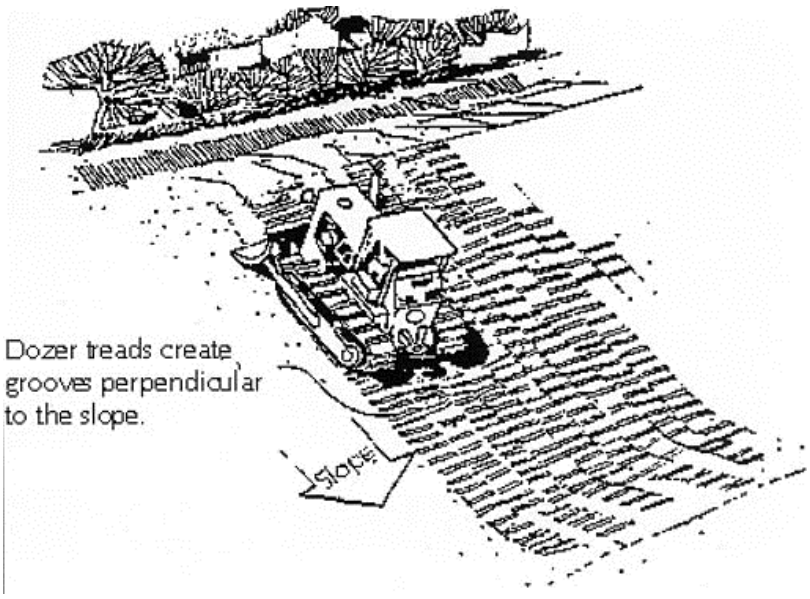


Figure 4a. *Track-walking slope roughening ESC technique*

Figure 4b. *Imprinting slope roughening ESC technique*

Figure 4c. *Sheep's-foot grading slope roughening ESC technique*

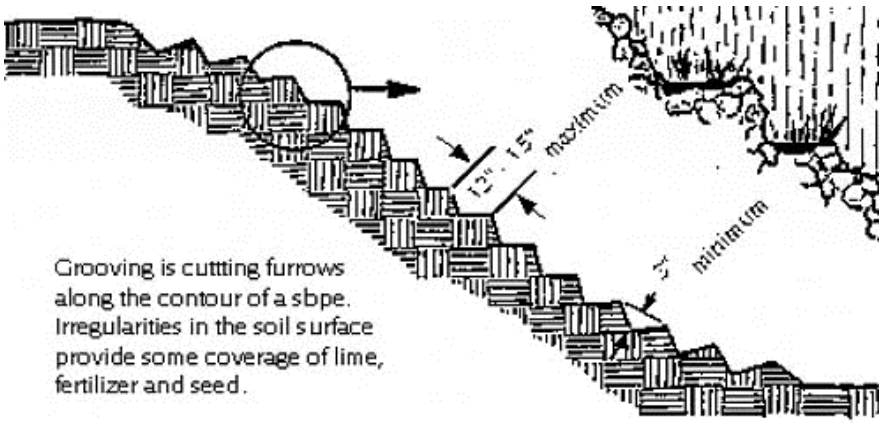


Figure 4d. *Grooving*

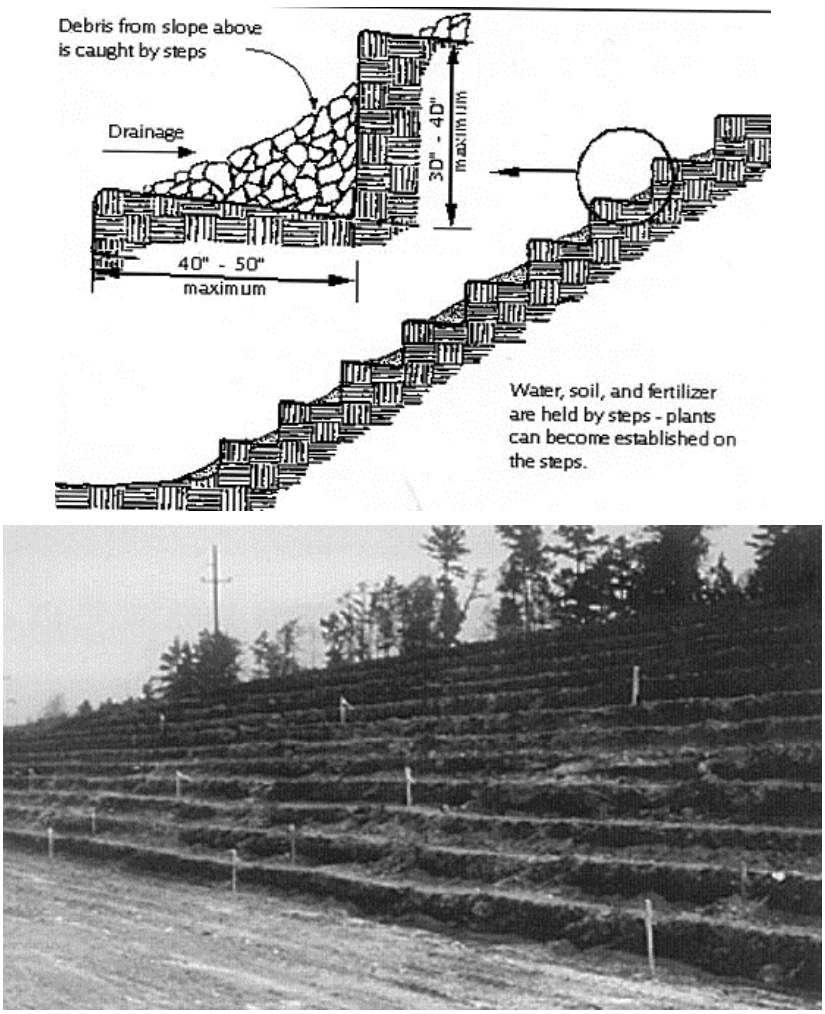


Figure 4e. *Stair-stepping*

Sediment Barriers

The use of straw bales, silt-fence, and other materials as barriers to sediment run-off or for soil erosion control is a common temporary ESC practice for construction sites. These BMPs may also have application for military-unique disturbance sites (training areas, OBOD sites, etc.).

Straw or hay-bale dikes are one of the most common ESC sediment barriers used. These BMPs are temporary structural BMPs constructed of rectangular hay bales tightly butted together, embedded four inches into the ground, and staked to the ground (Figure 5). Hay-bale dikes are designed only to temporarily impound or divert water and not filter it. Instead sediment is removed from run-off via settling. Heavier, coarse sediments are settled out by the impoundment of water. The bales are too dense and generally not tall enough to act effectively as filters devices. As with all ESC BMPs, proper use and installation techniques are critical to optimum performance.

Hay bale dikes should be used only for small (< 1 acre) areas of low flow (< 0.5 cfs). They are appropriate for areas where concentrated flows are very low and enough upgrade storage capacity is available so that run-off is not likely to overflow the top of the hay bales, and, on areas of sheet flow, such as slopes and graded areas, where a series of these dikes may be placed cross-slope on the contour with ends turned upslope to prevent flow around them. They may also be used in drainage channels as a sediment barrier, but should not be used for flow energy dissipation. Hay bale dikes usually require closer spacing as land or channel gradients increase. This is necessary to create more storage and induce more sedimentation, and thus prevent or reduce the potential of flow over-topping the bales. Erosion on the backside of the hay bale structures, created from over-topping energy, may negate erosion control benefits created with the front-side settling of sediments.

Hay-bale dikes should be used during seasons of low intensity storms and in areas where protection from sediment erosive water flow is needed for durations of less than 3 months. Examples include the following:

1. Small construction sites/locations where individual structural BMPs are being constructed such as drop inlets, permanent grade stabilization structures, pipes, and culverts. Hay bales are typically removed when work is completed or shortly thereafter.
2. Hay-bale dikes may be used in seeded or sod areas where erosion is a problem and where aesthetics is not a concern. Where the structure creates no adverse conditions, hay-bale dikes may be left in place after vegetation is established. Whenever possible, however, the sediment buildup from the front (upstream) side of the dike should be removed after every significant sediment-depositing event. Do not allow sediment to accumulate closer than 6 inches of the top of the lowest hay bale. Re-secure and tighten all hay bale dikes after every rainfall event and replace damaged bales immediately
3. Hay-bale dikes can also be used as a sediment barrier in temporary drainage channels or around the perimeter of a work area.

As with other temporary sediment barriers, hay-bale dikes need to be installed prior to major vegetation and soil disturbance activities. Hay-bale dikes are appropriate for use where the slope does not exceed 2:1 and where the perpendicular flow path length is less than 100 feet. Proper installation includes entrenching the bales to a depth of at least 4 inches and backfilling them on the upstream side with compacted soil (see Figure 5). There should be no gaps between bales and all bales should be staked down using metal rebar or wooden posts (18 inch minimum depth below the bales).

During the period of use, hay-bale dikes must be inspected frequently (at least weekly and before and after major storm events). Maintenance and replacement should be performed promptly to ensure effectiveness is optimized. Damaged bales should be replaced immediately and captured sediment should be removed after each storm or during periodic inspections. In all cases, do not allow sediment to accumulate to within 6 inches of the top of the dike. When the site has been stabilized, the dike can be removed.

In recent years, the utility and effectiveness of hay-bale dikes has been questioned. This BMP has been around for quite a while and there may be more effective techniques that will accomplish the same objectives (*Luytens*, 2001). Some of the most promising, new sediment control devices include the following:

1. Excelsior "sediment logs"
2. Straw-rice "wattles"
3. Reinforced geo-textile silt barriers

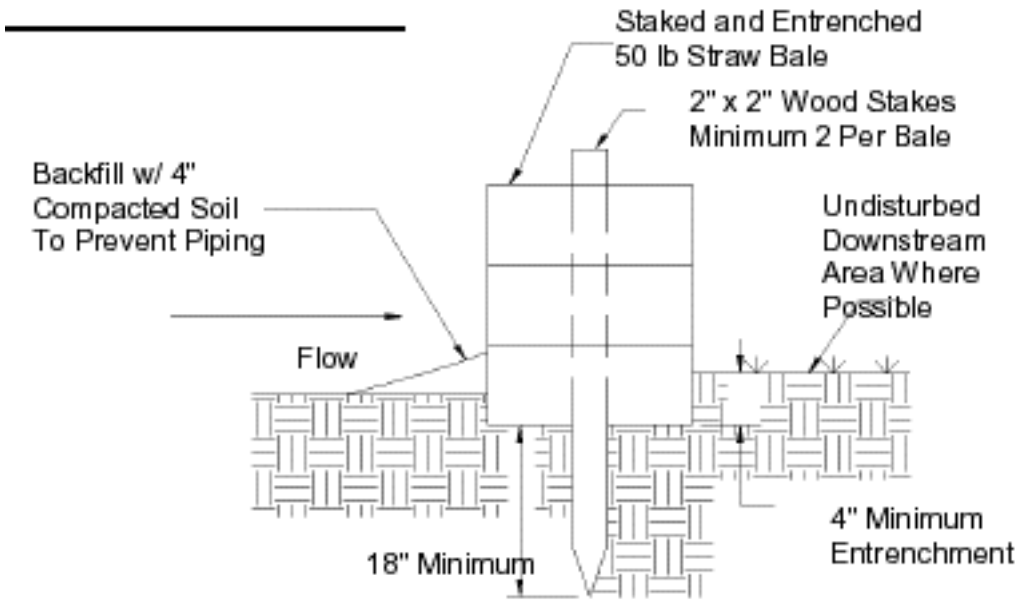


Figure 5. *Proper installation of a hay-bale dike*

Brush barriers are similar to hay-bale dikes in their purpose and application. A brush barrier is a temporary sediment barrier that is constructed from materials accumulated on

site during clearing and grubbing operations. It is typically constructed at the bottom perimeter of a disturbed area and is often used as a backup sediment barrier for silt fencing and/or a hay-bale dike. In some cases, filter fabric or silt fence material is incorporated into the brush barrier to enhance filtering efficiency (Figure 6). Like silt fences and hay-bale dikes, brush barriers should only be used for small (< 1 acre) sites where the surface run-off is primarily sheet-flow (< 0.5 cfs). Brush barriers are not recommended for sites with slopes over 2% and should not be used in channels or swales. Wood chips or mulch should not be included in the brush barrier because of the possibility of long-term leaching into run-off flow. However, there has been some success using compost material as a filter berm in a similar fashion to the brush barrier just described (*Tyler*, 2001). The combination of compost material in a berm and a brush barrier may also be quite effective. The barrier should be inspected frequently and repaired promptly when failures are noted. In addition, sediment buildup behind the barrier should be removed after every large storm event. When the site has been stabilized, the filter fabric can be removed and the remaining brush allowed to decompose naturally.

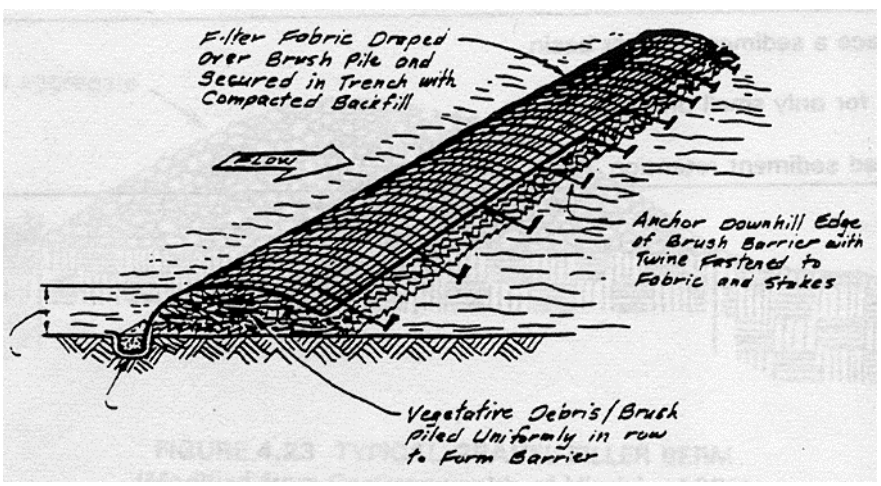


Figure 6. *Brush barrier basic design and installation*

<u>Gravel or stone filter berms are another commonly employed temporary ESC BMP</u>. These rock "rip-rap" berms are constructed along topographic contours to filter run-off, collect sediment, slow sheet flows, and divert surface flows away from specific areas. The most common use for these temporary rock berms is to divert run-off from vehicular traffic paths so as to limit sediment transport by construction vehicles. In addition to rock berms, "rip-rap" pads or entrance areas are often used at construction sites to encourage sediment removal from vehicles prior to leaving the site. This technique could also be used at the exits from training areas or OBOD sites on military bases. Berms should be constructed of well-graded crushed rock and should be spaced based on the steepness of the slope (closer together for steeper slopes). As with other temporary sediment barrier BMPs, these structures should be inspected frequently (especially after major storms) and repaired promptly.

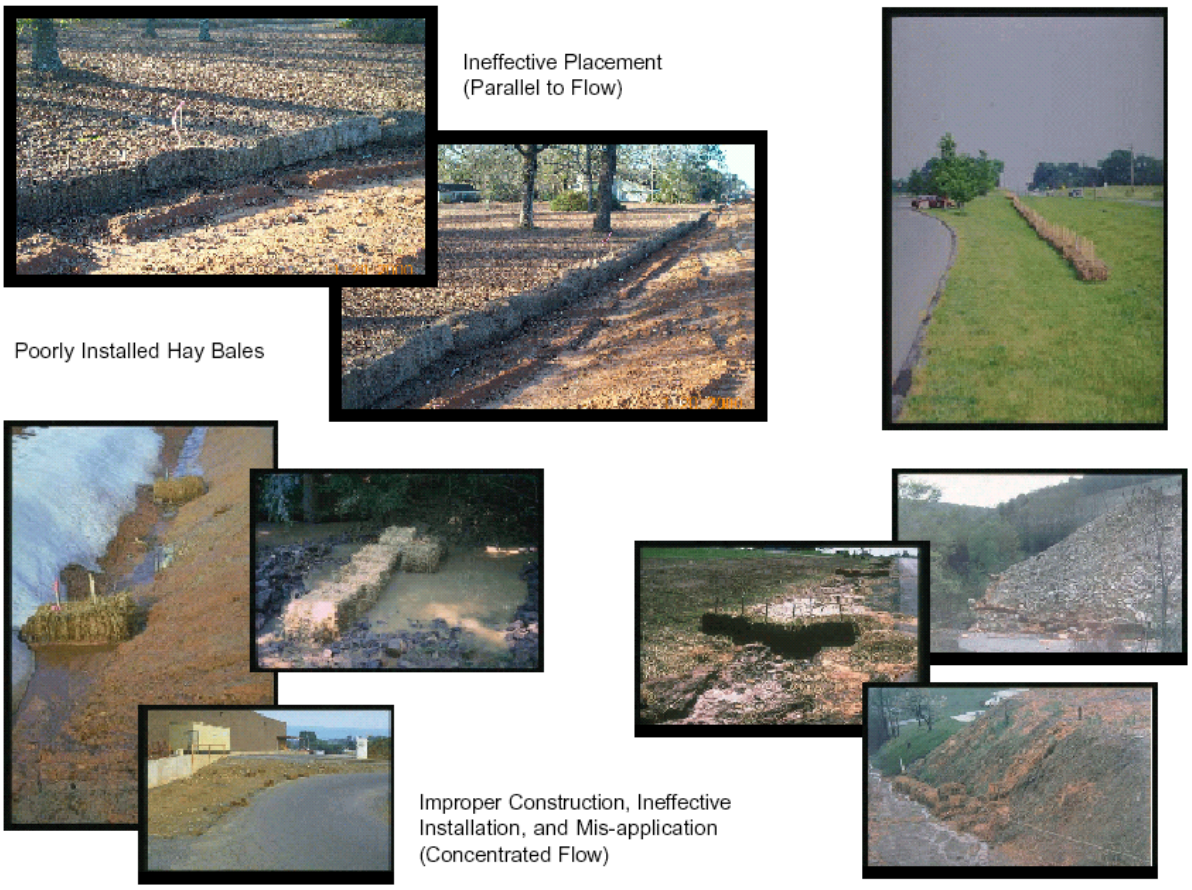


Exhibit 6.1a - Improper use and/or installation of hay bale dikes.

Exhibit 6.1b - Proper use and/or installation of hay bale dikes.

Figure 7. *Examples of proper and improper installation of hay-bale dikes*

Silt fence is another very common ESC BMP. Silt or filter fencing is a temporary structure constructed of pervious geo-textile fabric supported vertically by steel or

wooden posts (Figure 8). Silt fencing is not an erosion-control BMP. It is designed to slow, temporarily impound, and filter sediment-laden water from construction sites or other temporarily disturbed sites. Silt fencing typically has a useful life span of approximately 6 months. These ESC BMPs should only be used for small drainage areas (< 1 acre). Sediments are settled out by the impoundment of water and filtered by the fabric. Effectiveness of filtration diminishes with sedimentation sealing the fabric pores over time.

Three types of geo-textile material are commonly used for silt fencing: woven fabric, woven monofilament, and non-woven fabric. The woven monofilament geo-textile fabric tends to be the strongest. In some situations, wire-mesh backing support should be utilized to reinforce the silt fencing (14-gauge wire mesh with a 4 inch mesh-size is recommended). Permeability of silt fence material is measured by the effective opening size (EOS). The EOS is equivalent to the standard US sieve size criteria. In general, the selection of silt fence material should be a balance between retention of sediment particles and unimpeded drainage of water. Generally an EOS of between 70 and 100 is used. In any case, if 85% or more of sediment particles (by weight) can pass through a US standard sieve No. 200, then do not use silt fencing.

Silt fence may also be used to redirect runoff instead of impounding it. Silt fencing is most effective where surface run-off is sheet flow. The installation technique and proper maintenance are critical to performance. Silt fencing should be used only in areas of low flow rate (< 0.5 cfs) where concentrated flow volumes are low, and enough upgrade storage capacity is available where run-off will pond, then filter through the fabric or infiltrate, and not overflow the top of the fence. Because of potentially high flows, silt fencing should not be used where slopes exceed 1:1. The maximum flow path length leading to a silt fence should not exceed 100 feet perpendicular to the silt fence. The lower edge of the silt fencing must be vertically entrenched to a depth of 6-12 inches, backfilled with gravel, and then covered with soil. Post-spacing should be between 6 and 10 feet, depending on the site conditions and posts should be set at least 18 inches deep. Silt fence material is typically 3 feet in width. See Figure 9 for installation details. Silt fencing may also be used to reduce wind-blown sand from being blown off site.

Common use areas include slope toes and outlets where sheet flow from slopes and graded areas can potentially carry sediment off site. Multiple silt fences should be considered for highly erosive sites or sites upstream of sensitive aquatic resources. Silt fence filters usually require closer spacing as site gradients increase. This is necessary to create more storage and induce more infiltration, and thus prevent or reduce the potential of flow over-topping the fence. Silt fence can be used in areas where protection from sediment and erosive water flow is needed for an extended period of time. Examples include:

1. Large or small sites where individual structural BMPs are being constructed such as,drop inlets, permanent grade stabilization structures, pipes, or culverts.
2. At the perimeter of disturbed areas where run-off leaves the site. Typically used at the toe of a slope as the final sediment barrier around the site.
3. Silt fence may be used in seeded or sod areas where erosion is a problem and where aesthetics is not a concern. Where the structure creates no adverse

conditions, silt fences may be left in place after vegetation is established. Whenever possible, however, the sediment buildup from the front (upstream) side of the fence should be removed after every significant sediment-depositing event.

During the period of use, silt fence must be inspected frequently (at least weekly and before and after major storm events). Maintenance and replacement should be performed promptly to ensure effectiveness is optimized. In all cases, do not allow sediment to accumulate closer than half way to the top of the lowest point in the fence. Re-secure and tighten fencing and fabric after every significant run-off event, especially checking the toe of the fabric for breaches. When the site has been stabilized, the silt fence can be removed.

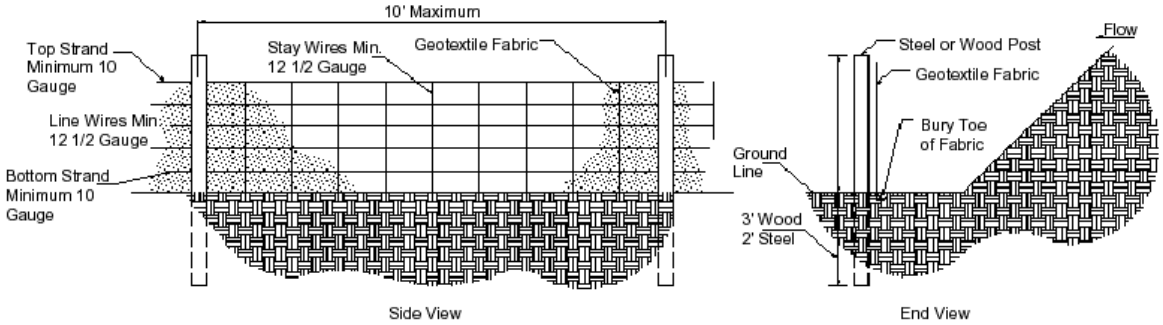


Figure 8. *Proper installation arrangement for silt fence*

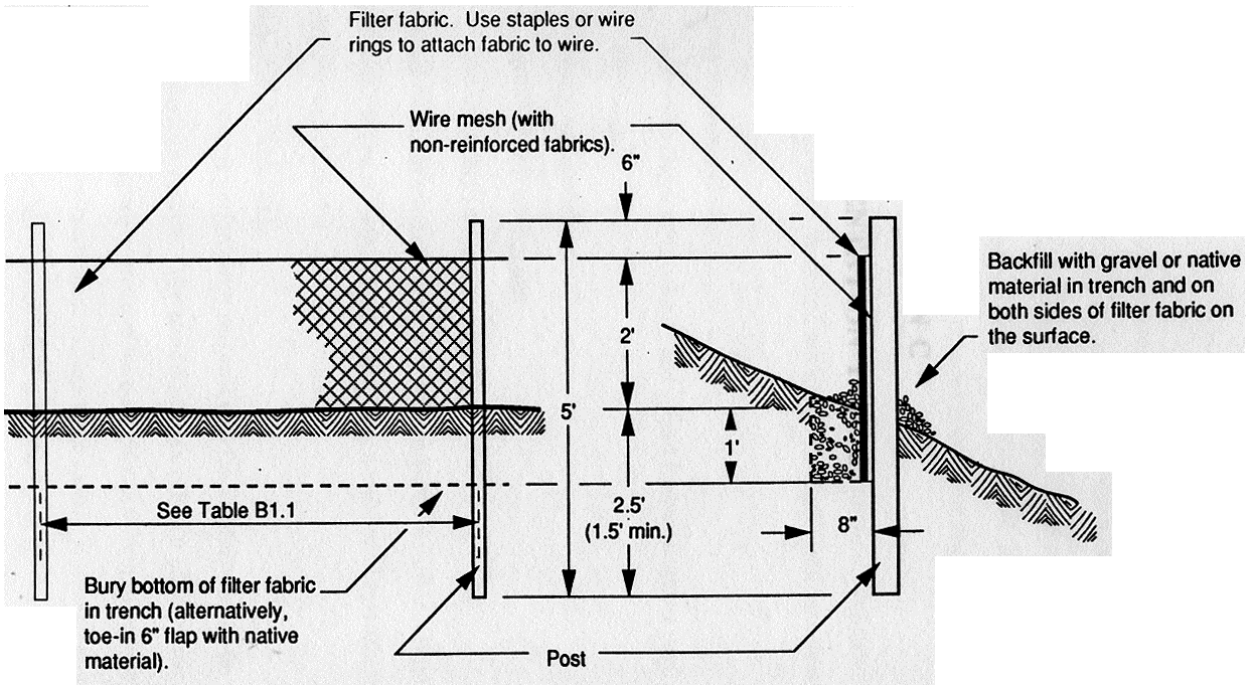


Figure 9. *Silt fence installation details*

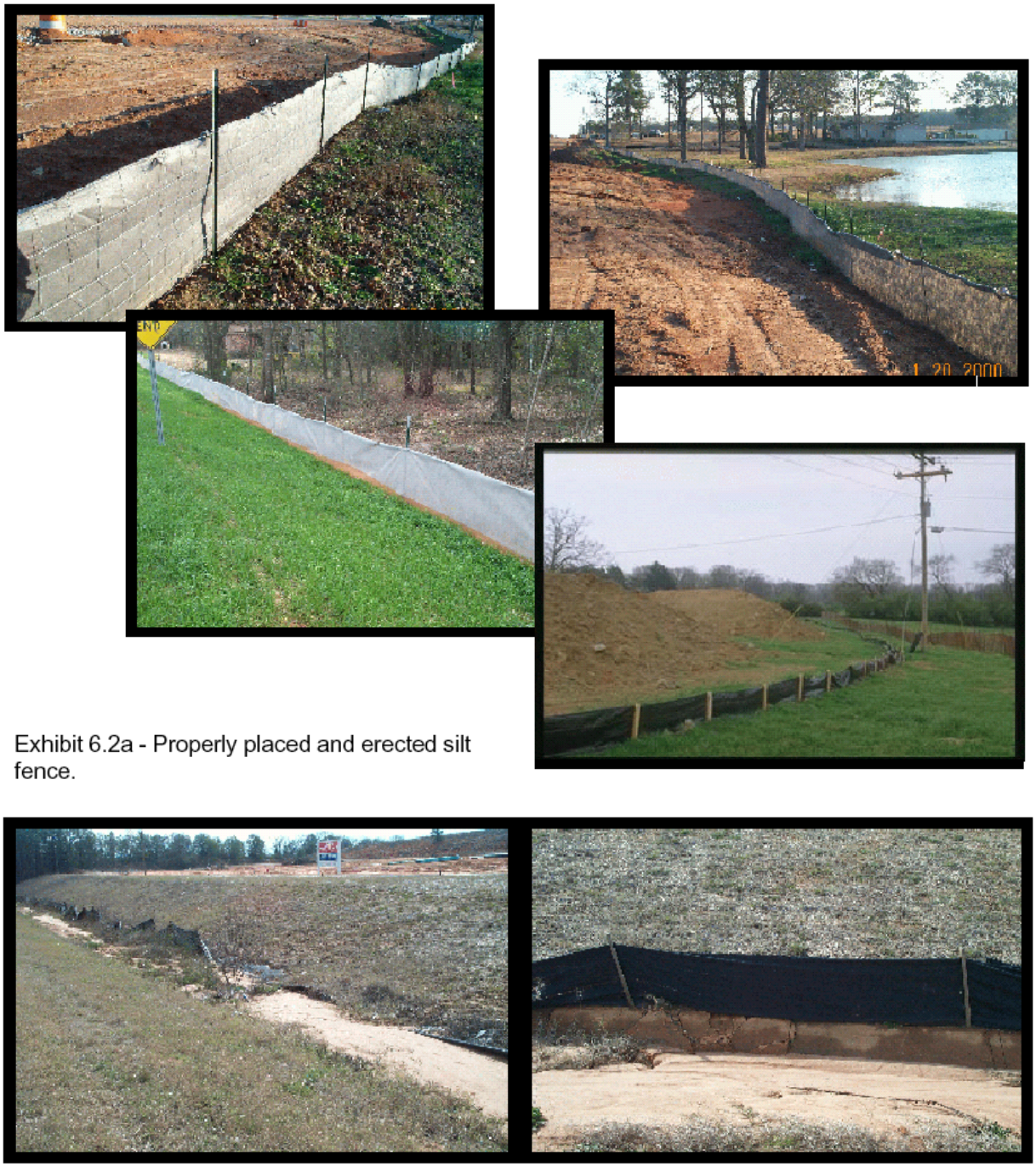


Exhibit 6.2a - Properly placed and erected silt fence.

Figure 10. *Examples of properly and improperly installed silt fencing*

Erosion Control and Energy Dissipation BMPs

Channels, ditches, and swales are often used to route run-off away from disturbed sites or sensitive natural resources. These channels can be prone to erosion and sediment production if flows are too high and/or concentrated, especially in situations where the

gradient is steep. A reduction in run-off velocity will reduce erosion potential and often prevent gully formation. The use of "rip-rap", level-spreaders, and check dams is common in erosion control practice in the private and public sectors. These BMPs may also have application for military-unique disturbance sites (i.e., training areas or OBOD sites).

Rock check dams are one the most common ESC sediment barriers used in this country. These structures can be temporary or permanent structural BMPs, constructed of crushed stone of various sizes, depending on the application (Figure 11). A check dam will eddy water behind it, settle out sediment, and allow water to pass through and/or over its crest. Once sediment has filled in behind the structure the active function of collecting sediment will cease, however, it will continue to act as a stabilizing force for the channel or ditch bottom grade.

These BMPs are often used in permanent roadside ditches as well as temporary run-off channels or swales. The roadway crown, shoulder, and ditch bottom elevations must be maintained constant for as long as possible to extend the life of these structures and make them cost effective. Unchecked roadway degradation renders these stationery structures useless and may allow them to become accelerants to erosion rather than aids against it. For optimum performance, these structures must be designed by a professional engineer, meticulously installed, and rigorously maintained. Structures must be embedded into the side banks, toed into the channel bottom at the outlet, and have a flow channel deep enough to handle normal run-off to minimize the potential for over-flow scour around the edges. Also, there should be enough outlet apron to dissipate the energy of water overflowing the crest to protect the toe from the undermining scour that can lead to failure. A toe-wall at the end of the apron is often necessary. Continual maintenance is critical until the structure has stabilized and "seated" itself.

Lateral run-off from adjacent roadway surfaces or back slopes must be directed safely into the ditch or structure to prevent washout along the edges of the structure. Construct the structure of stone large enough, or otherwise secured in place, to resist expected velocities. A geo-textile fabric or aggregate filter should lay between all stone to ground contact surfaces, with overlap at fabric seams, and fabric or aggregate overlapping the exposed edges at the surface as shown in Figure 11. Multiple check dams should be spaced such that the toe of the upstream dam is at the same elevation as the top of the next downstream dam. Gabions (wire-mesh boxes filled with rock) are a similar type of erosion control BMP that can be used as a check dam or parallel to the flow path for side-slope erosion protection.

Check dams should be inspected periodically and after every significant rainfall event. The inspection should focus on dam-edge breaches or dam failures as well as sediment and debris accumulation. Sediment should be removed before the depth upstream of the dam is greater than one-half the original dam height. Debris should be removed immediately to prevent dam bypass of concentrated-flow erosion.

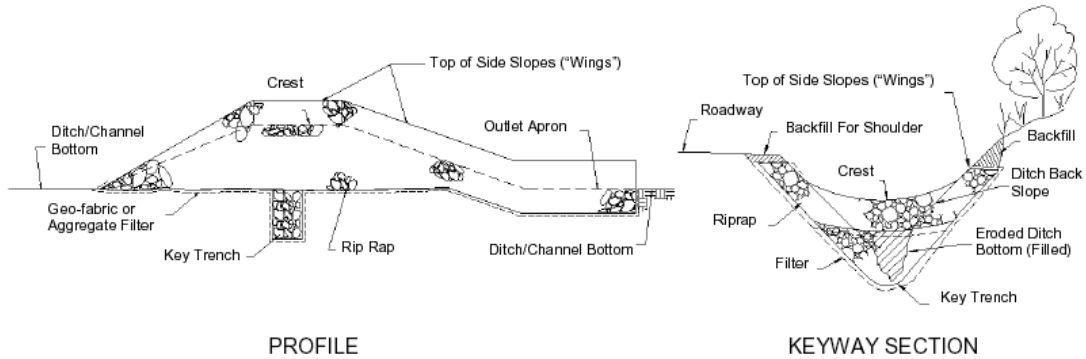


Figure 11. *Rock check dam*

Level spreaders are another common ESC technique. These structures can be temporary or permanent structural BMPs, constructed of crushed stone of various sizes, depending on the application. Level spreaders are used to spread run-off into sheet flow and discharge flow over a wide area so as to dissipate energy, remove silt from the run-off, and direct flow into another ESC device. This structure reduces concentrated flow, increases infiltration, and allows for sediment to be removed by settling and filtering. Level spreaders are generally used at the toe of a slope, but can be used to intercept concentrated run-off and disperse it across the head (top) of a slope or grade. This application can be useful in protecting road banks from concentrated flow entering from upland drainage areas. A level spreader is constructed as a water impounding channel or trench, cut on a level contour into a slope or grade. The front (down-slope) edge allows shallow discharge over its entire length when the impoundment is full. The impoundment should be shallow, but deep and wide enough to reduce surface turbulence from the run-off inflow allowing the water to evenly fill the impoundment and then flow smoothly over the discharge point along the front edge no deeper than 1/2" at peak design flow. The impoundment will catch sediment and will require periodic clean-out maintenance.

Passive filtration systems or barriers are another category of sediment control BMPs. These devices are strictly temporary. The purpose of this ESC measure is to prevent sediment run-off from entering the permanent stormwater drainage system during soil disturbing activities. Hay-bales, straw or excelsior "wattles" and a variety of commercially available devices are acceptable for this purpose (*Hull*, 2001).

Outlet protection is another erosion control BMPs. These structures can be temporary or permanent structural BMPs, constructed of crushed stone of various sizes, depending on the application. Outlet protection should be installed at the outlets of culverts, swales, and ditches where the flow velocity could cause erosion in the receiving channel. Outlet protection acts to dissipate flow energy and settle out sediment particles. Outlet protection should be installed early in the site disturbance process, but can be added as required at any time.

Gravity-based sediment settling BMPs, sediment traps or basins, are often used to control sediment on disturbed sites such as construction sites. These BMPs are typically temporary in design, but may be semi-permanent. The use of "sediment traps" and "sediment basins" is common in erosion control practice in the private and public sectors.

These BMPs may also have application for military-unique disturbance sites (i.e., training areas or OBOD sites). It should be stressed that source control is the most effective method for reducing erosion and sediment transport, but in some cases it is necessary to have a backup system to deal with the problem. Sedimentation traps and basins serve this purpose. Figure 12 shows a typical sedimentation basin.

A sediment trap is a temporary basin created by either excavation, earth or rock embankment, or a combination of these to intercept, trap, and retain sediment from run-off while allowing detained run-off to slowly drain, infiltrate, or both. Sediment-laden run-off can be drained and filtered by perforated pipe, rock filtration and/or rock dam seepage, infiltration, or a combination of these. These structures are usually used during construction or maintenance practices. They are easily and economically constructed and offer versatility of location. Materials used to construct them can be demolished and constructively used or disposed on site when the structure's service area has been adequately stabilized. Because of the predominantly temporary nature of these structures, they usually require removal of collected sediment after each run-off event to restore adequate operating capacity and are constructed with an emergency bypass for excessive run-off events.

A sediment basin is a semi-permanent to permanent version of a sediment trap constructed by either excavation, embankment, or a combination of these to intercept, trap, and retain sediment from runoff while allowing detained runoff to slowly drain, infiltrate, or both. These structures, illustrated in Figure 12, are used for indefinite periods of sediment collection associated with long-term disturbance of the earth such as mining, farming, unpaved road drainage, etc. Sediment and run-off storage capacities are often larger than sediment traps, and embankments are usually constructed of more permanent materials such as compacted earth, rock, concrete, etc. A professional engineer experienced in hydrology should be consulted for design of these structures. Ideally, sediment basins should be elongated in the direction of flow with the length at least twice the width to obtain the most effective settling of sediments. Depth should be determined based on length and width dimensions and volume requirements for run-off storage plus sediment retention. Consideration may be given to outflow and/or infiltration versus inflow in determining run-off detention volume. If possible, a sedimentation basin should have a 5:1 length to width ratio and side-slopes should be 3:1 or flatter. Basin depth should be limited to less than 5 feet so as to avoid anaerobic conditions that can limit effectiveness. If feasible, the basin should be divided into two or more cells so as to increase the flow path and enhance sedimentation. If a multi-cell design is not possible, structural baffles can be used for the same purpose.

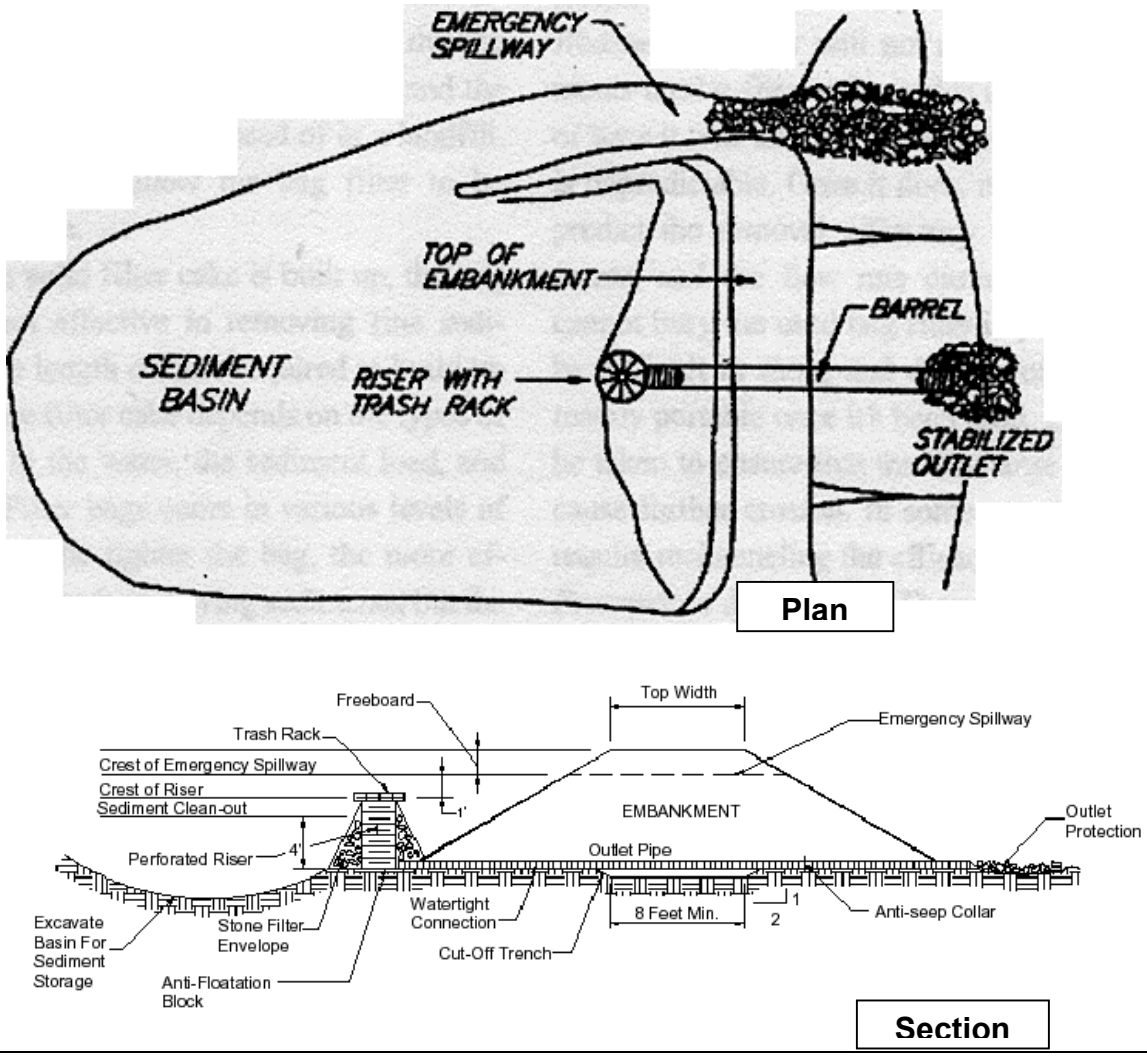


Figure 12. *A typical sediment basin*

Sediment-laden run-off can be drained and filtered by perforated pipe, rock filtration, rock dam seepage, infiltration, pumping, or a combination of these. Three "clean water" drainage or discharge methods are described below.

1. Riser pipe and barrel outlet - The top section of risers are most often perforated, but may not be, depending on storage volume of the basin, percolation/recovery rate, probable peak run-off volumes, other basin drainage mechanisms, or any combination of these.
2. Rip-rap or aggregate filter dam - This porous dam is constructed at least one foot higher than height at maximum design run-off retention volume. Run-off will drain through rip rap and/or coarse aggregate leaving behind sediment. Rock in the dam may need cleaning and re-mixing to improve permeability when in use for extended periods or when frequent, sediment-laden discharges have entered the structure. By-pass is usually the top of the dam.

3. Under-drain filter outlet - An aggregate-shrouded pipe network buried at the bottom of the basin, this system is for a more elaborate structure and works best where the basin is constructed in sandy soils. May be used in conjunction with other discharge methods.

In general, sediment basins are effective at settling the larger sediment particles, but are usually ineffective in removing fine sediment. This is a major weakness of gravity-based settling systems (*Gannon*, 1999). These BMPs also require a relatively large surface area to maximize effectiveness. When residence time is adequate, a reduction in turbidity, nutrients, metals, and other particulate-bound pollutants is possible. Typical removal efficiency for total suspended solids (TSS) is around 40-60%. These BMPs typically cost around $5K per acre served and have a service life of 6-8 months. This is relatively expensive for BMP with such low removal efficiency. Sediment removal and dewatering are the most common maintenance activities. Periodic inspections (at least weekly and after major storms) will determine the frequency of these operation and maintenance activities.

In recent years, the effectiveness of sediment basins has been improved through the use of polymer batch-treatment systems. In this method, *cationic* (+) and *anionic* (-) polymers are used to enhance the removal of fine sediments, clays, and other colloidal material from the run-off being detained in the sediment basin (*Tobiason et al.*, 2001). The mechanism for fine sediment removal is known as *flocculation*. Basically, the polymers cause fine sediment particles to attract, forming larger particles, which then settle out faster. Polymer is typically injected into the system prior to the sediment basin so that contact time is maximized. The use of polymer treatment is strongly recommended, especially for sediment basins located upstream of sensitive aquatic resources (*Minton and Benedict*, 1999).

Left Side Basin

Right Side Basin

Typical Sediment Basin Use on an Unpaved Roadway

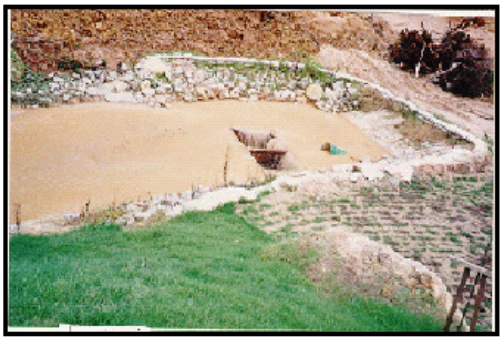


Figure 13. *Examples of sediment basin*

Permanent Erosion and Sediment Control

This section describes specific ESC measures designed for long-term deployment on erosion-prone sites after site-disturbing activities are complete or for sites where land-use activities cause permanent erosion or soil exposure. This later category includes military-unique activities such as combat training and OBOD operations. The methods discussed include native plant revegetation and "terra-forming". To a large extent, both of these

techniques utilize the natural ecosystem to provide long-term, low-maintenance, and effective erosion and sediment control.

Revegetation

The benefits of preserving native vegetation have already been discussed, however it is worth reiterating the positive impact this has on ESC. During the site planning process, areas of mature native vegetation, large trees, or other valuable (ecological or aesthetic) areas of native vegetation should be identified and every effort made to preserve them. This may require modification of site layout plans. In addition to native vegetation, native topsoil is also worth preserving. It is the combination of vegetation and the upper soil layers that maintains the natural hydrologic regime, minimizing erosion on undeveloped land. The maintenance of native topsoil also will enhance any revegetation efforts that are planned. Native topsoil contains the nutrients, organic matter (OM), and mycorrhizal fungi necessary for successful seed germination and growth (*Steinbacher*, 2001). This may require stockpiling topsoil on site during clearing operations, for use after development is complete.

It is recommended that a comprehensive pre-disturbance site assessment be done to establish natural baseline conditions (soil, vegetation, hydrology, aspect, topography, etc.) so that post-development plans are implemented in an environmentally responsible manner. The preservation of riparian vegetation is especially important to the long-term protection of aquatic resources. This applies equally to rivers, streams, wetlands, lakes, and coastal/estuary areas.

Site revegetation can be accomplished by transplanting, sodding, and/or direct seeding (*Steinbacher*, 2001). With either method, proper surface treatment and irrigation are the keys to success. Seeding should be mulched or RECP used on slopes greater than 4:1. In most cases, native vegetation works best, however in some situations, non-native vegetation will be a better choice. In some cases, aesthetic landscaping considerations take priority and in other cases, post-development site conditions will also favor non-natives. In either case, it is important to avoid the use of potentially invasive species. Native topsoil and OM/ mycorrhizal fungi addition will also enhance germination and growth. A permanent cover of vegetation will reduce erosion potential in the following ways:

1. By shielding the soil from direct erosion by rainfall
2. By improving the soil water storage and infiltration capacity
3. By slowing run-off and filtering sediment
4. By physically holding soil in place on slopes

Terra-Forming

"Terra-forming" describes a combination of permanent ESC measures that can be used for sites where long-term erosion problems are expected or where the potential for problems is high and where sensitive aquatic resources are at risk. This BMP uses the natural site topography to create a series of *interceptor berms* (ridge-dikes formed from compacted soil), *swales* (excavated depressions), and level-spreaders that alternate along

site contours (Figure 14). Run-off is routed through this sequence of bio-detention terraces, away from areas of higher erosion potential and sensitive resource areas. This technique is used to prevent up-slope run-off from causing erosion and sediment production by reducing surface flow velocities, maintaining sheet flow, and encouraging infiltration (*Murfee et al*., 1997). Typically terra-forming uses alternating, vegetated berms and swales to minimize erosion potential and maximize sediment deposition. The number of berms and swales required will depend on the terrain and surface area of the site. The vegetated berms and swales are designed to filter run-off through vegetation (biofiltration), remove sediment by deposition, and provide opportunities for infiltration. In most cases, rock berms may be used for up-slope contours instead of compacted soil berms (Figure 15). These initial screening berms should remove the bulk of the sediment from up-slope disturbed areas. The rock screening berms must be periodically cleaned of sediment. In all cases, the down-slope soil berms and swales should be permanently vegetated with native grasses or plants. In some cases, the lowest elevation swales may be constructed as a wetlands or wet swales for final "polishing" of run-off prior to discharge into receiving waters. This technique could be used effectively around the perimeter of some combat training areas or open-burning and open-detonation (OBOD) sites.

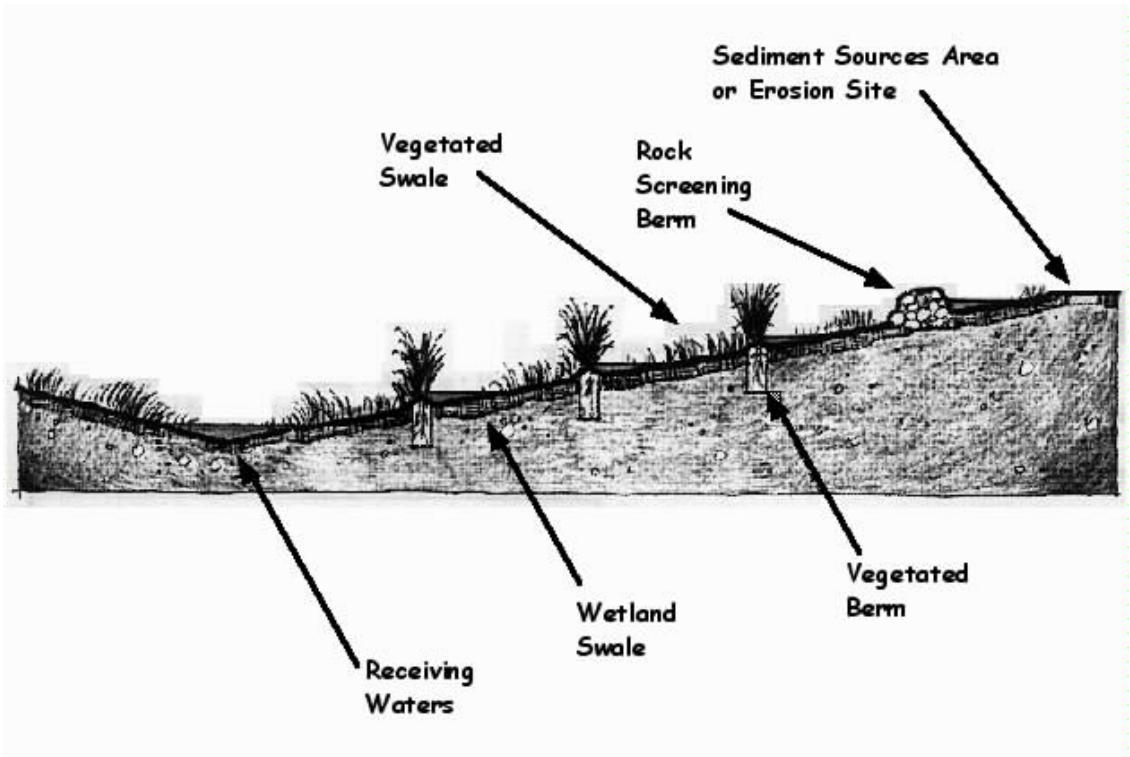


Figure 14. *Bio-detention terra-forming arrangement*

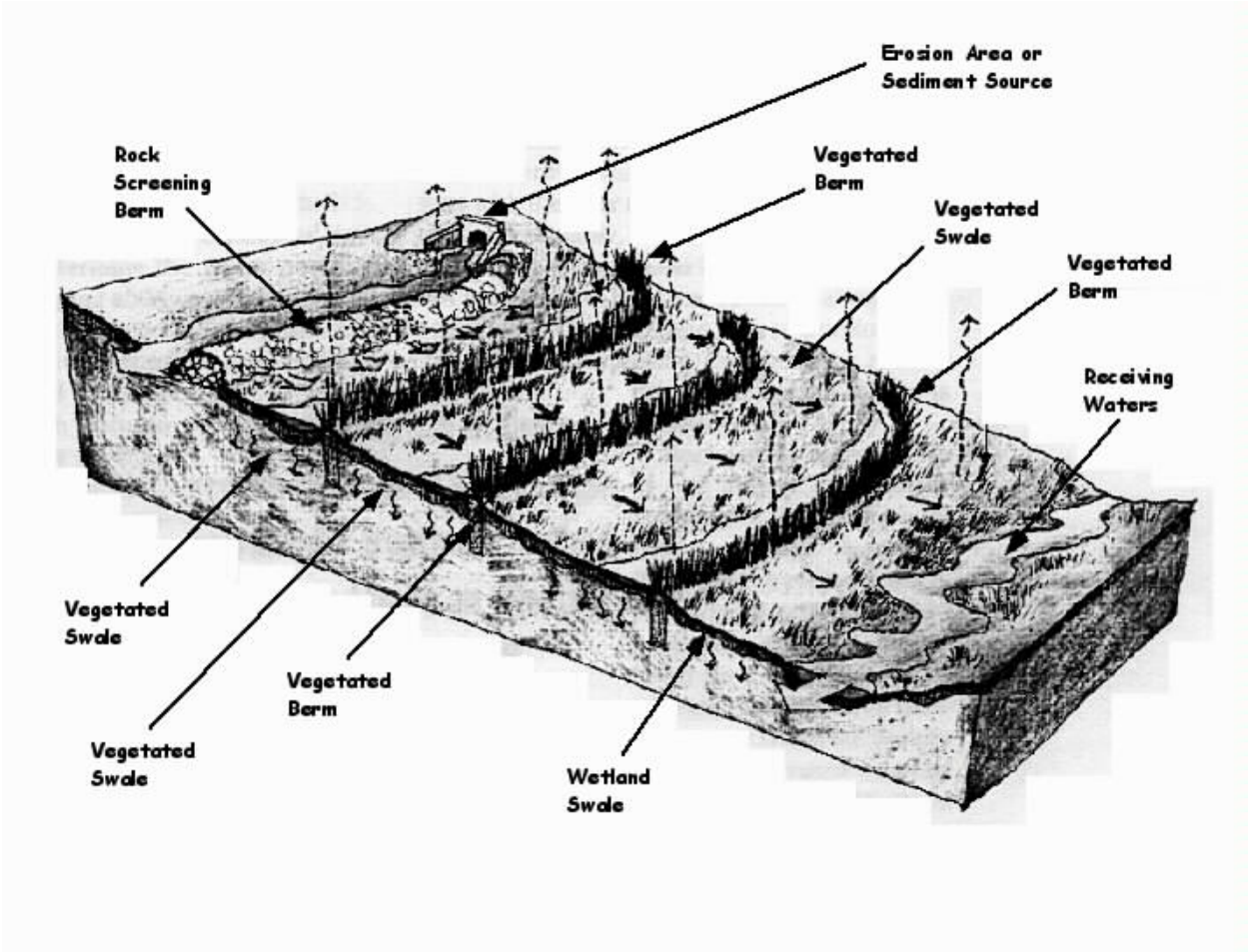


Figure 15. *Bio-detention terra-forming arrangement*

Table 1. *Biodegradable mulch soil stabilizers (BMSS) summary*

Type	**MATERIAL**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Cost/ Ha**
Straw Mulch	Wheat or Rice Straw	L	L	B	M	L	1	M	H	H	H	$5-6K
Excelsior Mulch	Wood Fiber	L	M	B	L	L	1	M	M	H	H	$1-2K
Wood Mulch w/Tacifier	Excelsior	M	M	B	L	L	1	H	M	H	H	$2-3K
Compost Mulch	Composted Vegetation	L	M	B	L	M	1	M	H	H	H	$1-2K
Recycled Paper Mulch	Cellulose Fiber	L	M	B	L	L	1	L	M	H	H	$1-2K
Paper Mulch w/Tacifier	Cellulose Fiber	M	M	B	L	L	1	M	M	H	H	$2-3K
Bonded Fiber Matrix	Biodegradable Fiber Mixture	M	H	B	M	L	1	M	H	H	H	$5-10K

Criteria

A = Site preparation requirements (L=low / M=moderate / H=high)

B = Mode of application (L=hand labor / M=mechanical blower / H=hydro-seeding)

C = Degradability (B=bio-degradable / P=photo-degradable / C=chemical degradable)

D = Residual impact on future site activities (L=low / M=moderate / H=high)

E = Potential impact on water quality (L=low / M=moderate / H=high)

F = Time between application and optimum effectiveness (days)

G = Longevity of effectiveness (L=1-3 months / M=3-6 months / H=6-12 months)

H = Erosion-control effectiveness (L=0-50% / M=50-75% / H=75-90%)

I = Availability on commercial market (L=low / M=moderate / H=high)

J = Ease of cleanup and waste disposal (L=low / M=moderate / H=high)

Table 2. *Rolled erosion control products (RECP) summary*

Type	**MATERIAL**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Cost/ Ha**
Jute Mesh	Jute Fiber	M	L	B	L	M	1	H	M	H	H	$10-15K
Wood Fiber Mesh	Excelsior	M	H	B	L	M	1	M	H	H	H	$20-25K
Curled Wood Fiber Blanket	Excelsior	M	H	B	L	M	1	M	H	H	H	$20-25K
Woven Straw	Straw	M	H	B	L	L	1	M	H	H	H	$15-20K
Coir Mesh	Coir Fiber	M	H	B	L	M	1	H	H	H	H	$25-50K
Coconut Blanket	Coconut Fiber	M	H	B	M	M	1	H	H	H	H	$20-30K
Straw-Coconut Blanket	Straw & Coconut Fiber	M	H	B	M	M	1	H	H	H	H	$20-30K
Plastic Mesh	Plastic	M	H	P	H	L	1	H	L	H	H	$5-10K
Plastic Sheeting	Plastic	M	H	P	H	L	1	H	H	H	H	$10-15K
Woven Geo-Textile Sheeting	Synthetic Fiber	M	H	P/C	H	L	1	H	H	H	H	$10-15K
Synthetic Fiber Mesh	Synthetic Fiber	M	H	P/C	H	L	1	H	H	H	H	$25-50K
Bonded Fiber Matrix	Fiber Mixture	M	H	P/C	H	L	1	H	H	H	H	$10-15K

<u>*Criteria*</u>

A = Site preparation requirements (L=low / M=moderate / H=high)

B = Mode of application (L=hand labor / M=mechanical blower / H=hydro-seeding)

C = Degradability (B=bio-degradable / P=photo-degradable / C=chemical degradable)

D = Residual impact on future site activities (L=low / M=moderate / H=high)

E = Potential impact on water quality (L=low / M=moderate / H=high)

F = Time between application and optimum effectiveness (days)

G = Longevity of effectiveness (L=1-3 months / M=3-6 months / H=6-12 months)

H = Erosion-control effectiveness (L=0-50% / M=50-75% / H=75-90%)

I = Availability on commercial market (L=low / M=moderate / H=high)

J = Ease of cleanup and waste disposal (L=low / M=moderate / H=high)

Table 3. *Hydraulically applied soil stabilizers (HASS) summary*

Type	**MATERIAL**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Cost/ Ha**
Hydro-seed w/tacifier	Mulch	M	H	B	L	L	10	H	M	H	H	$1-3K
Psyllium or Starch	Plant-based Material	M	H	B	L	M	10	M	M	M	H	$1-2K
Pitch/Rosin Emulsion	Plant-based Material	M	H	B	L	H	10	M	M	M	M	$1-3K
Polymeric Emulsion Blend	Acrylic or Hydro-colliod Polymers	M	H	P/C	L	L	5	H	H	M	M	$1-2K
Emulsified Petroleum Resin	Petroleum-based Material	M	H	P/C	M	H	5	H	M	L	L	$1-3K
Cementitious Binder	Gypsum	L	L/M	C	M	M	5	L	L	H	M	$1-2K

Criteria

A = Site preparation requirements (L=low / M=moderate / H=high)

B = Mode of application (L=hand labor / M=mechanical blower / H=hydro-seeding)

C = Degradability (B=bio-degradable / P=photo-degradable / C=chemical degradable)

D = Residual impact on future site activities (L=low / M=moderate / H=high)

E = Potential impact on water quality (L=low / M=moderate / H=high)

F = Time between application and optimum effectiveness (days)

G = Longevity of effectiveness (L=1-3 months / M=3-6 months / H=6-12 months)

H = Erosion-control effectiveness (L=0-50% / M=50-75% / H=75-90%)

I = Availability on commercial market (L=low / M=moderate / H=high)

J = Ease of cleanup and waste disposal (L=low / M=moderate / H=high)

Table 4. Soil surface roughening techniques summary

Type	**GRADIENT LIMIT**	**Operational Complexity**	**Erosion-Control Effectiveness**	**Cost/ Ha**
Smooth-Rolled	3:1	Moderate	Poor	$2-3K
Ripped		Low	Good	$3-5K
Track-Walked	3:1	Low	Good	$3-5K
Imprinted	2:1	Moderate	Outstanding	$1-2K
Sheep's-foot Rolled	3:1	Moderate	Excellent	$3-5K
Grooved	2:1	High	Excellent	$5-10K
Stair-Step Graded	> 2:1	High	Outstanding	$5-10K

Low Impact Development

Parking Lots

Best Management Practice Fact Sheet

Background

Under the conventional development scenario, temporary storage spaces for motor vehicles (parking lots and on-street parking), along with roads, can make up a significant portion of the total watershed area. Sixty to seventy percent of the total impervious area (% TIA) in a typical suburban watershed can be in the form of transportation related impervious surfaces. In that parking areas are usually constructed with asphalt or concrete surfaces, they also tend to be highly connected to the stormwater drainage infrastructure. As a result, these impervious areas can contribute a significant quantity of stormwater run-off to the natural drainage system. In addition, because motor vehicles parked on these impervious surfaces tend to leak oil and other petroleum hydrocarbon products, as well as depositing heavy metals and other pollutants, parking areas are a major collector and conveyor of urban non-point source (NPS) pollution. This polluted run-off can degrade downstream receiving water quality.

Problem Description

The standard parking stall occupies between 160 and 180 square-feet of space. This may not seem like much in the way of impervious surface area, but when combined with travel lanes, driveways, ramps, curbs, median islands, handicap spaces, and overhang space, the average parking lot can require up to 400 square feet of space per vehicle, or about 1 acre of impervious surface per 100 cars (*BASMAA*, 1999). In addition, most communities have established a minimum parking ratio (typically expressed as the number of parking spaces that must be provided) based on the particular land-use being serviced. This is usually stipulated as a minimum number of parking spaces per gross floor area for commercial, industrial, retail, and institutional land uses. Depending on the developer and the building occupant, the actual parking ratio can be much higher than the minimum required. In most cases there is a great deal of excess parking provided. This is especially true of retail centers, where parking may be based on the highest expected seasonal occupancy rather than the average level.

Recommended Solutions

There are many ways to both reduce impervious surface area associated with parking lots and to treat stormwater from these areas prior to it reaching downstream aquatic resources. As a start, communities can re-evaluate their current parking ratio minimums and establish maximum parking ratio limits based on land use or other appropriate criteria. This action can go a long way towards reducing/minimizing total impervious area within a watershed. In addition, parking codes can be modified to encourage the use of mass transit and/or to facilitate shared parking arrangements between adjacent land uses with differential parking requirements. Another option is to require the construction of multi-level parking garages to minimize impervious surface area while maximizing available parking.

Creating a new parking lot using LID principles or retrofitting an existing parking lot to reduce stormwater impacts can be accomplished using a variety of BMP techniques. Perhaps the greatest reduction in overall imperviousness can be realized through the use of permeable surfacing materials for parking areas. Permeable surfaced stalls are designed for stationary or slowly moving vehicles. For travel lanes and entry/exit driveways it is probably best to utilize standard asphalt or concrete. The use of alternative, permeable surfaces in a standard parking lot can reduce overall imperviousness by 60% or more and can reduce the need for costly underground stormwater infrastructure. There are many possible combinations of pervious and conventional surfaces that can be used depending on the parking lot configuration, traffic levels, and the permeability of underlying soils. Figure 1 shows two typical design layouts. The differentiation between parking stalls and travel aisles can also mitigate some of the visual impact of a large parking lot. Incorporation of shade trees, bioretention cells (rain gardens), and biofiltration swales can also improve aesthetics while also improving stormwater quality. Another option available for retrofit situations is installing permeable surfaces in just the "overflow" parking areas. This may be especially effective in applications where there is typically a high parking turnover or high traffic levels that might be ideal for permeable surfaces, but where there may be a substantial number of parking spaces that are normally unused except during seasonal, peak periods (Figure 3).

The specific selection of the type of permeable parking area surface and the design of the parking lot, including stormwater run-off treatment BMP configuration, will depend a great deal on the site characteristics and land-use requirements. There are several permeable surface options (Figure 4). Installation costs for permeable surfaces tend to be about 50% more than conventional surfaces, however the savings on stormwater piping, detention vaults, and curb and gutter infrastructure can be considerable. In almost all cases, extensive sub-grade preparations are required and under-drain or overflow drainage systems may also be necessary to deal with run-off from a range of storm sizes. In addition, some type of stormwater treatment will likely be needed to treat run-off from impervious travel lanes and associated buildings. These must be integrated into the overall site design. Operational and maintenance considerations for permeable parking areas include periodic sweeping, pressure washing, or vacuuming to remove fine sediment that can potentially clog permeable surfaces, weed control, litter pick-up, and periodic repairs. The operation and maintenance costs for permeable parking surfaces are comparable to standard pavement upkeep.

In addition to parking lots, residential sites can utilize some of these same BMPs to reduce run-off volume and enhance stormwater quality (Figure 5).

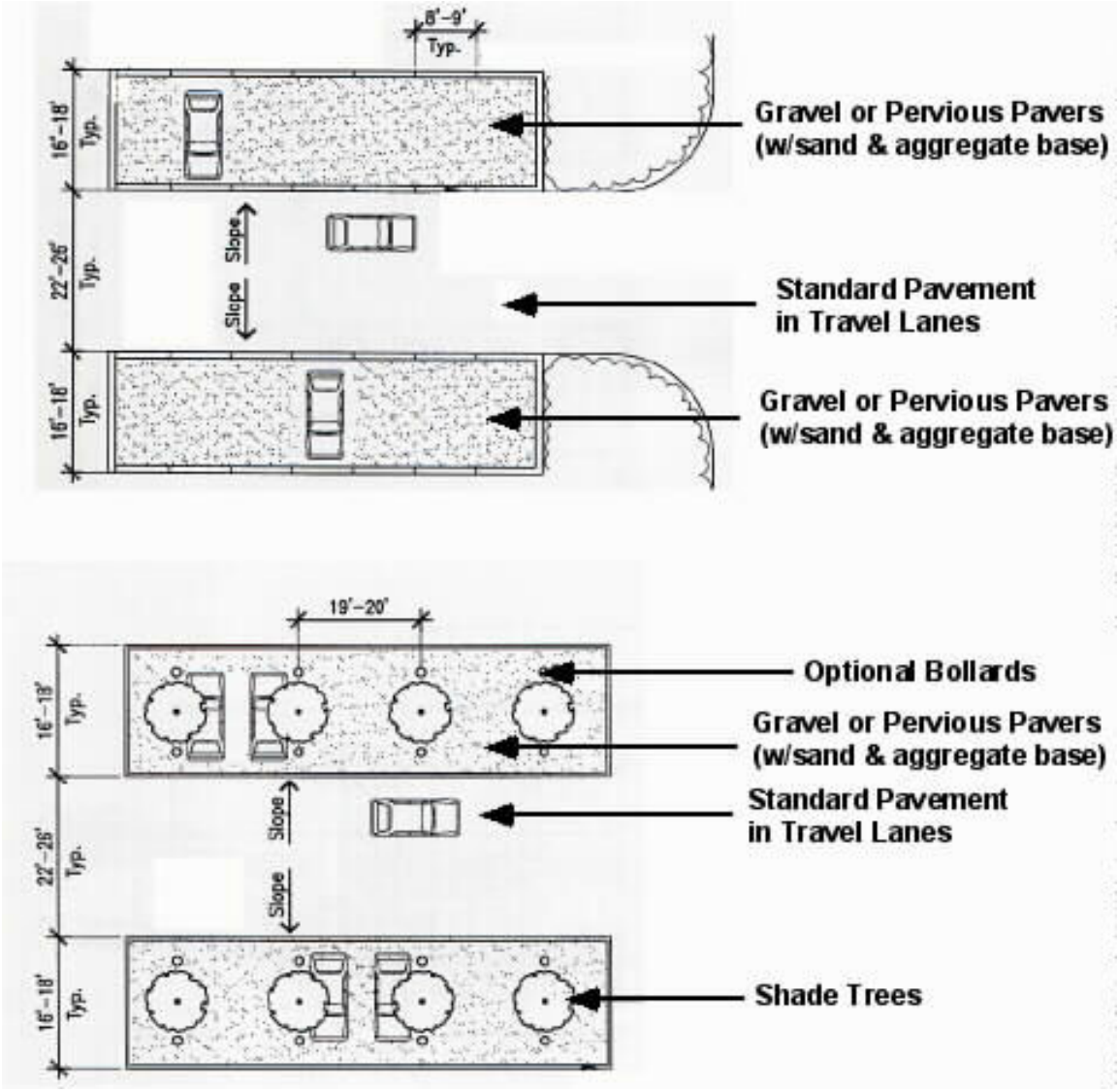


Figure 1. *Potential designs for LID parking areas*

Figure 2. *Typical parking lot bioretention cell configuration*

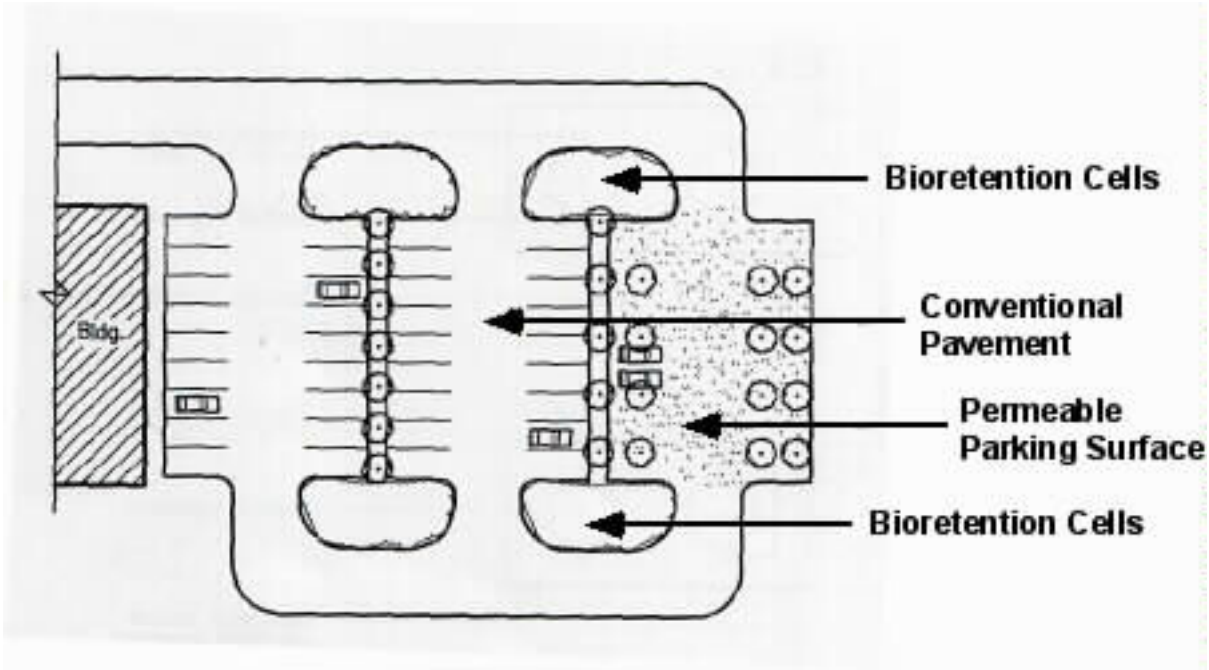


Figure 3. *Typical overflow parking lot configuration*

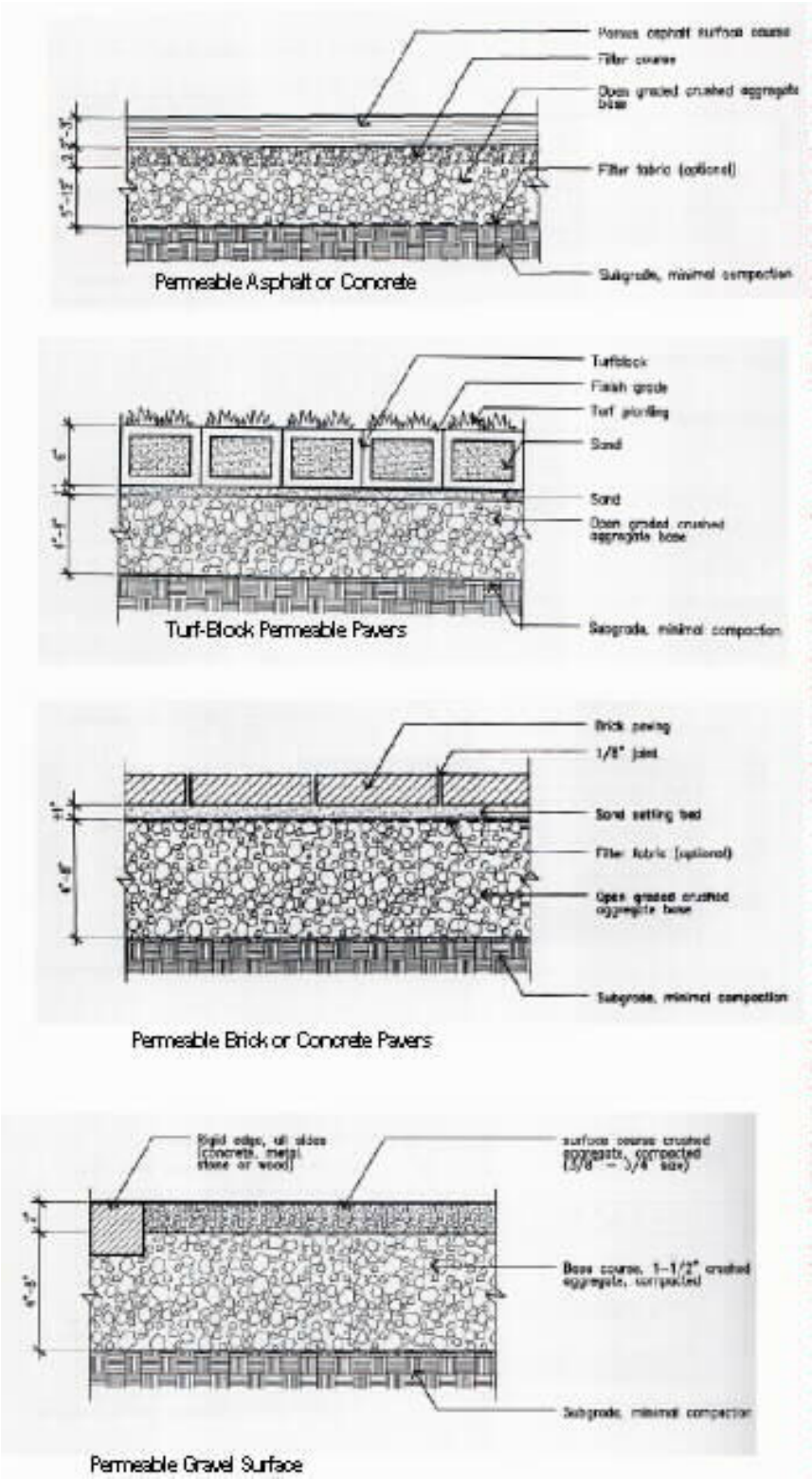
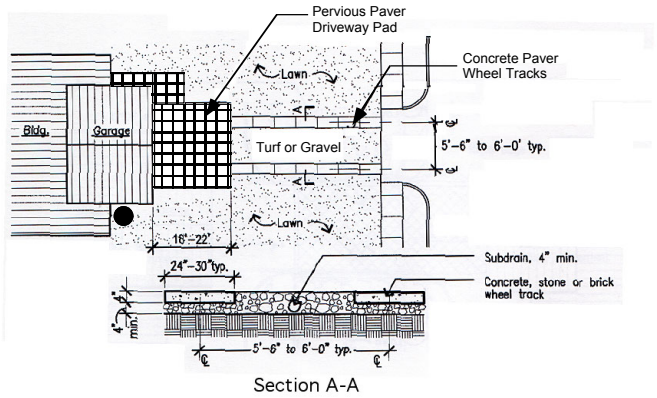
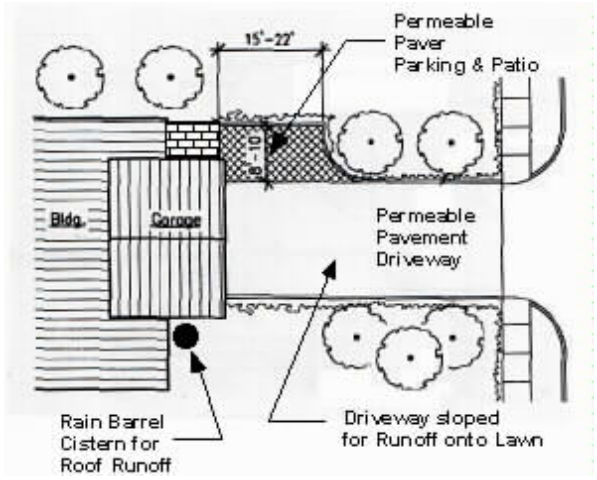


Figure 4. *Permeable surface design options*





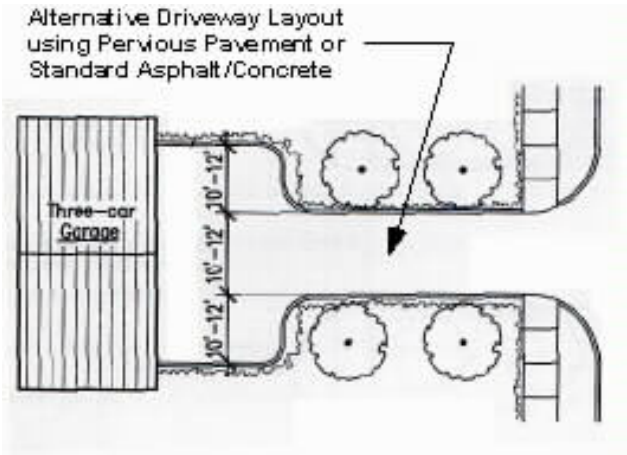


Figure 5. *LID driveway design layouts*

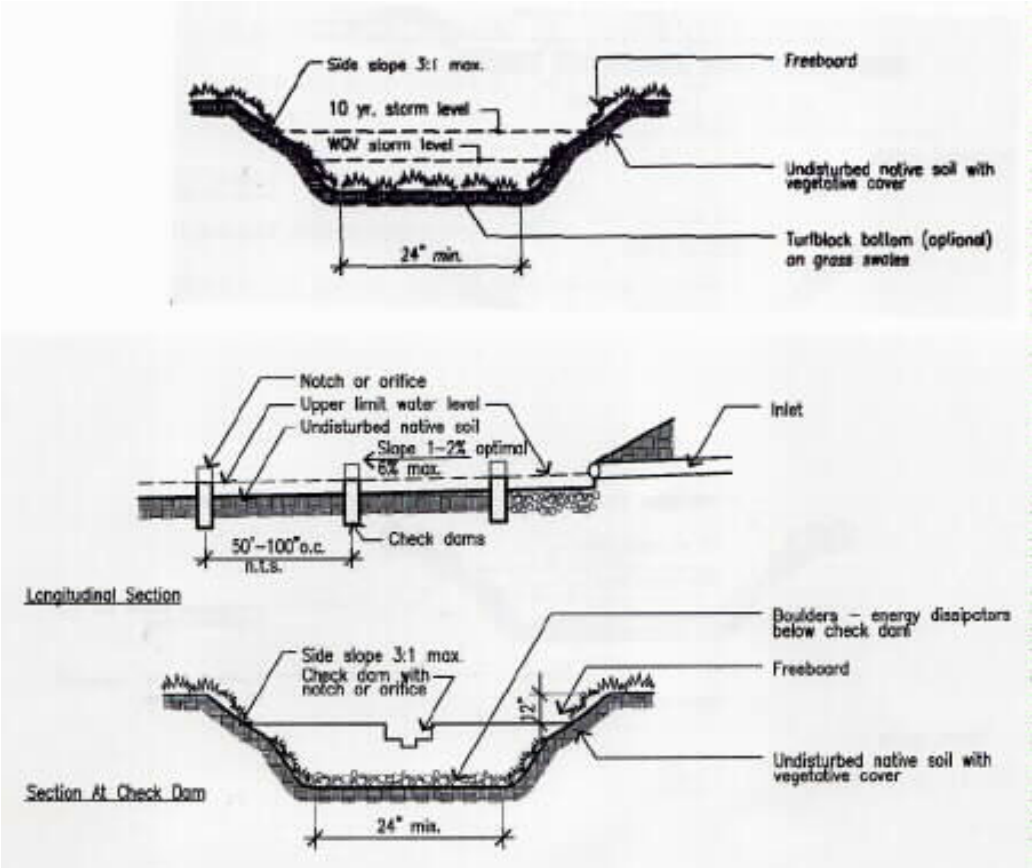


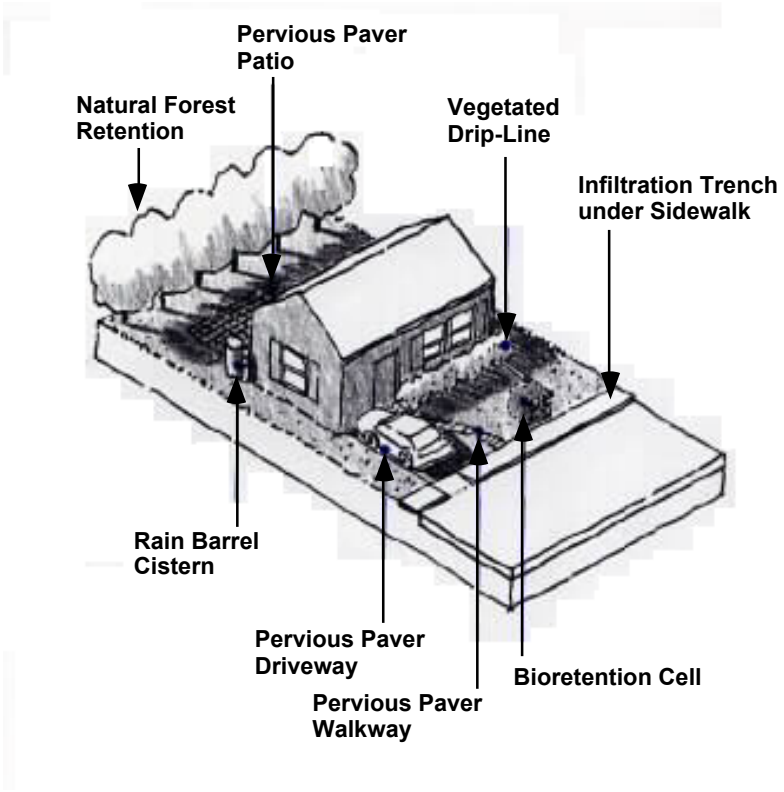
Figure 6. *Biofiltration swale design*

Figure 7. *LID driveway design*

Low Impact Development

Residential Site Layout

Best Management Practices Fact Sheet



Objectives

Residential lots provide numerous opportunities to reduce stormwater run-off and improve stormwater treatment. In addition to the stormwater management (SWM) benefits, these landscape and site design modifications also have aesthetic benefits for residents, such as backyard shade, supplemental irrigation water, and enhanced wildlife habitat. The exact suite of BMPs that are applicable to a specific site will depend on the site layout (lot size, adjacent lots, street configuration, etc.) and characteristics (soils, gradient, forest area, etc.). These LID SWM techniques can be used for single-family home sites (Figure 1) or multi-family developments (Figure 2).

The overall goal is to integrate stormwater management into a functional landscape design. This is as important on the development scale as it is on the site level. Incorporating LID stormwater treatment features into new housing developments or retrofitting LID into existing housing areas is critical in the overall watershed approach to stormwater management. Many LID best management practices (BMPs) are much more efficient when designed and constructed for a sub-division or street than for individual lots. There is also an economy of scale that can be realized for joint SWM projects as opposed to individual site facilities. In addition, the effectiveness of an integrated

stormwater treatment approach is significantly higher than for independent, individual designs (Figure 3).

LID Residential Applications

Numerous potential applications for LID BMPs are appropriate for residential situations on military bases. Family housing areas are the most obvious example of this. Another potential site-level application is the bachelor enlisted or officer quarters (BEQ/BOQ). Figure 4 shows a typical LID BMP layout for a BEQ/BOQ facility.

LID Techniques

The following LID BMPs can be used in residential situations:

- Rooftop and driveway run-off disconnection
- Biofiltration swales and filter-strips
- Forest retention or buffer
- Bioretention cells or rain gardens
- Rain barrels or cisterns
- Permeable pavement or pavers for driveways and sidewalks
- Concave lawn area with infiltration basin
- Lawn and garden soil amendment
- Shared driveways

BMP Operations and Maintenance

Property owner education is critical for the long-term success of LID stormwater BMP operations. Residents must understand the purpose of each BMP, how the individual BMPs fit into the overall site design, and how to optimize the performance of each BMP. In addition, basic maintenance must be clearly understood and carried out at the prescribed frequency. Most LID techniques are relatively simple and require no special operation and maintenance procedures. Periodic inspections of each BMP during storm events and under non-storm conditions will normally detect any problems. Grass used in biofiltration swales and vegetated filter strips must be maintained at a height of 6–8 inches. Infiltration devices and permeable surfaces must be protected from sediment/silt deposition that could potentially clog them. Rain barrels and cisterns should be cleaned periodically and kept covered so as not to become a vector problem. All BMPs should be kept clean and free of litter or debris.

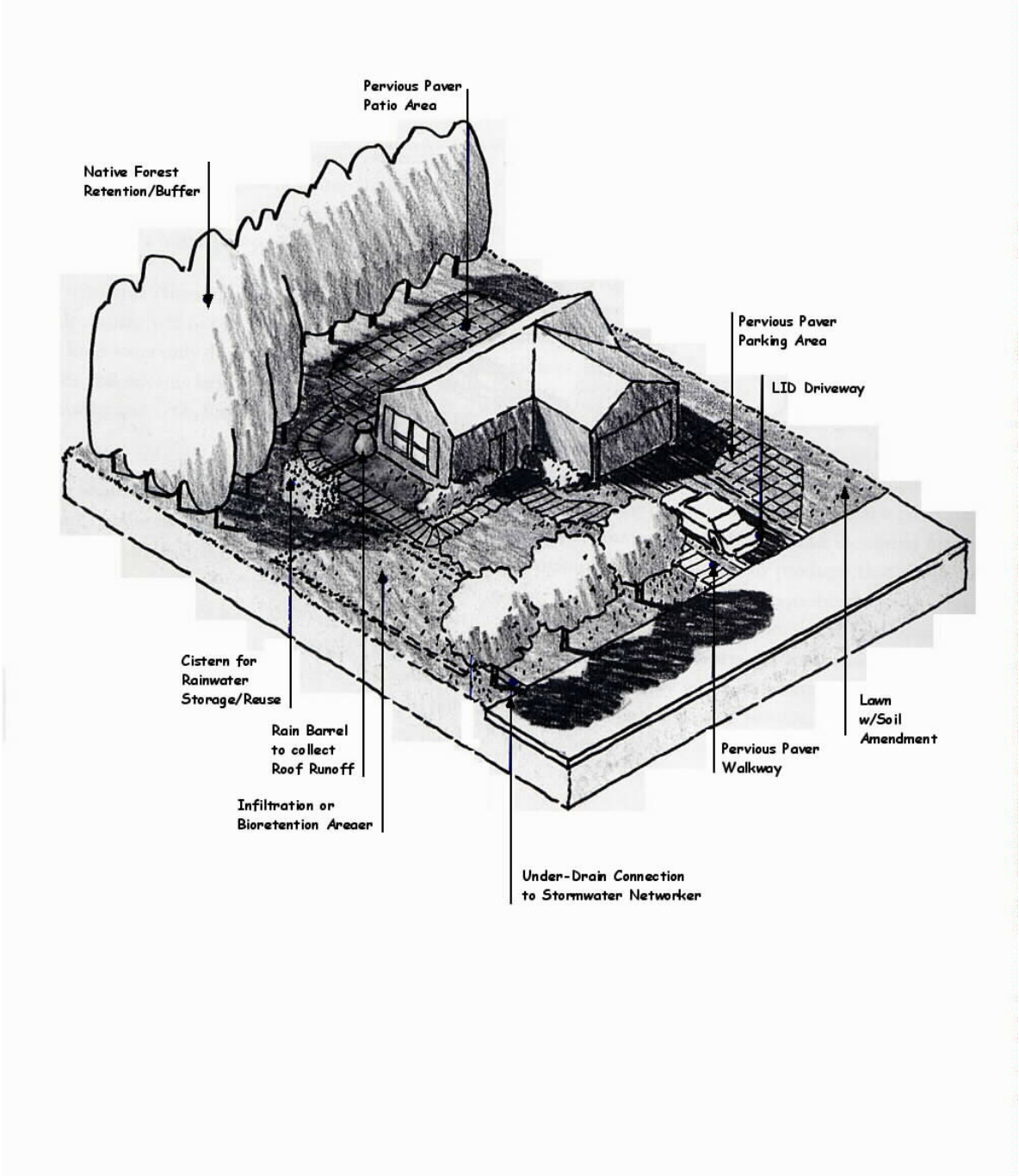


Figure 1. *Single-family residential LID site layout, showing potential BMP applications (modified from* BASMAA*, 1999)*

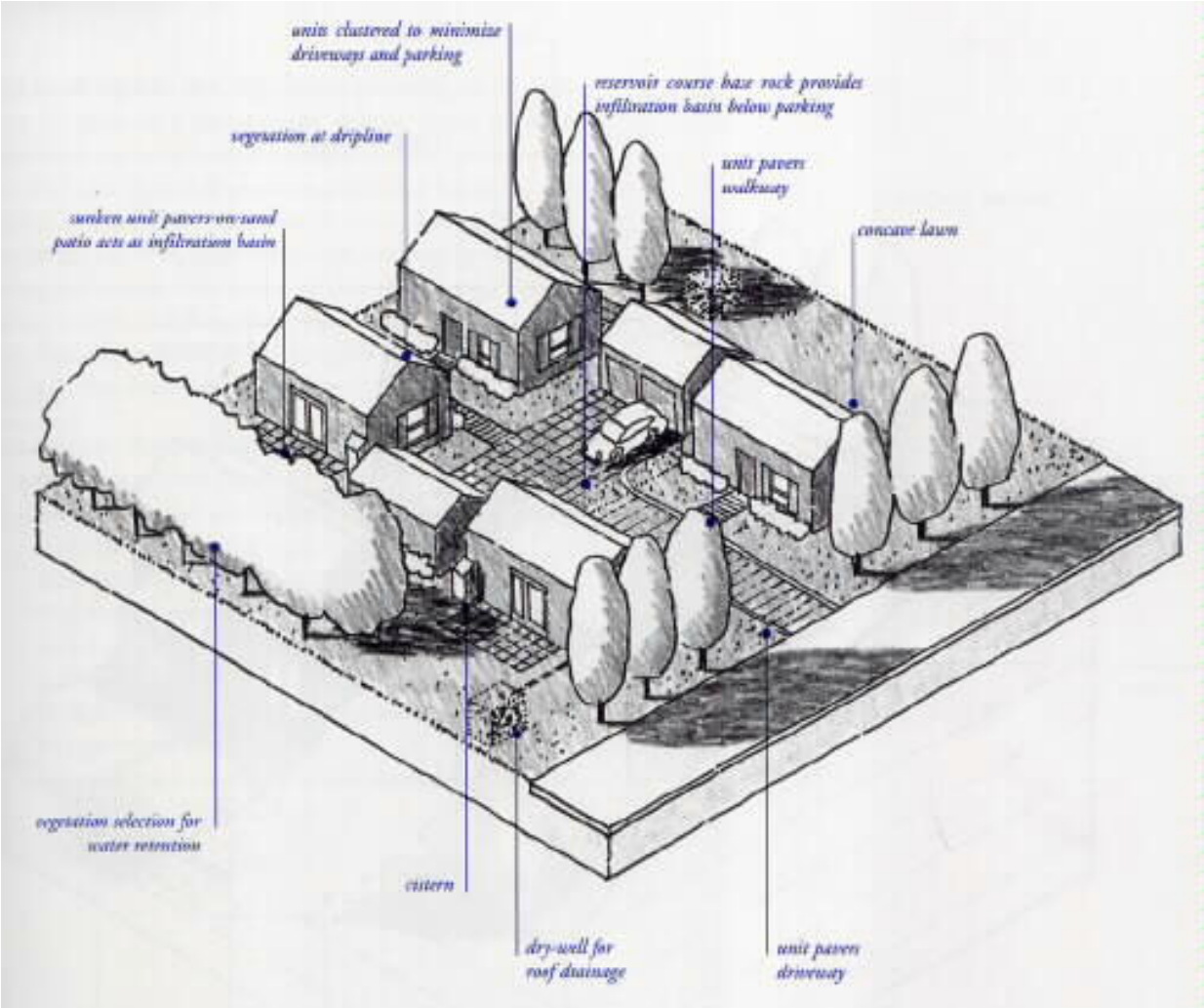


Figure 2. *Multi-family residential LID site layout, showing potential BMP applications (*BASMAA*, 1999)*

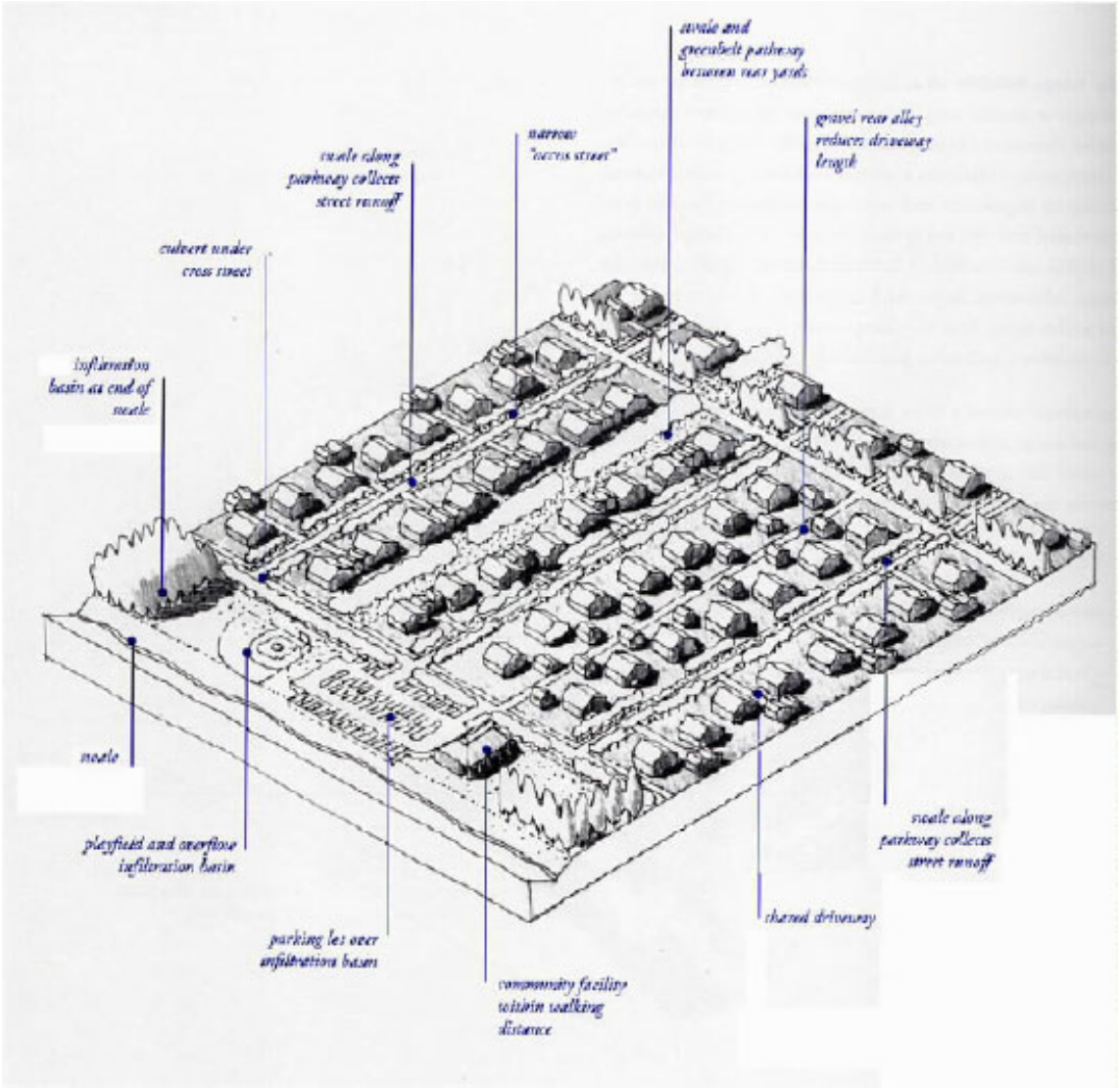


Figure 3. *Integrated residential LID site layout, showing potential BMP applications (*BASMAA*, 1999)*

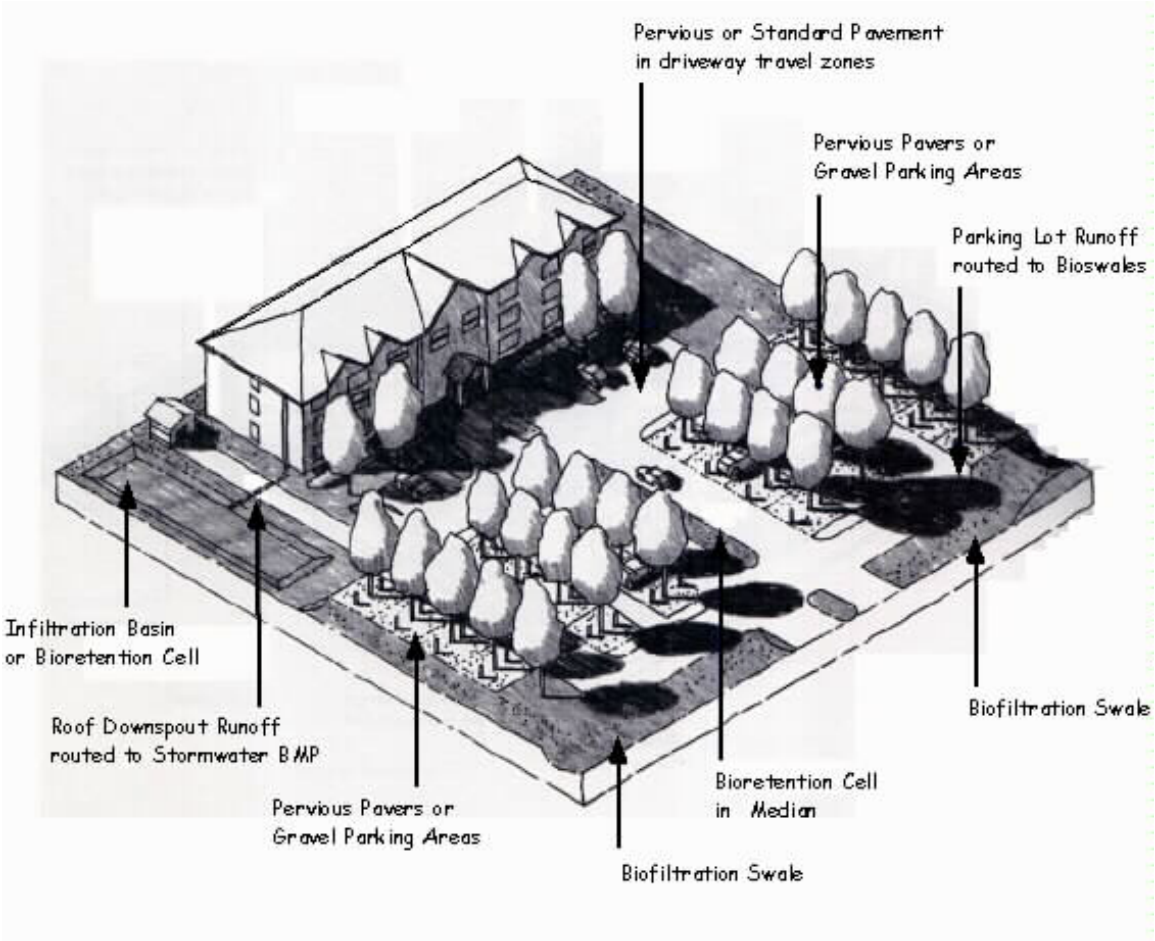


Figure 4. *Integrated LID site layout for a BEQ/BOQ complex or multi-story apartment building, showing potential BMP applications (*BASMAA*, 1999)*

Low Impact Development

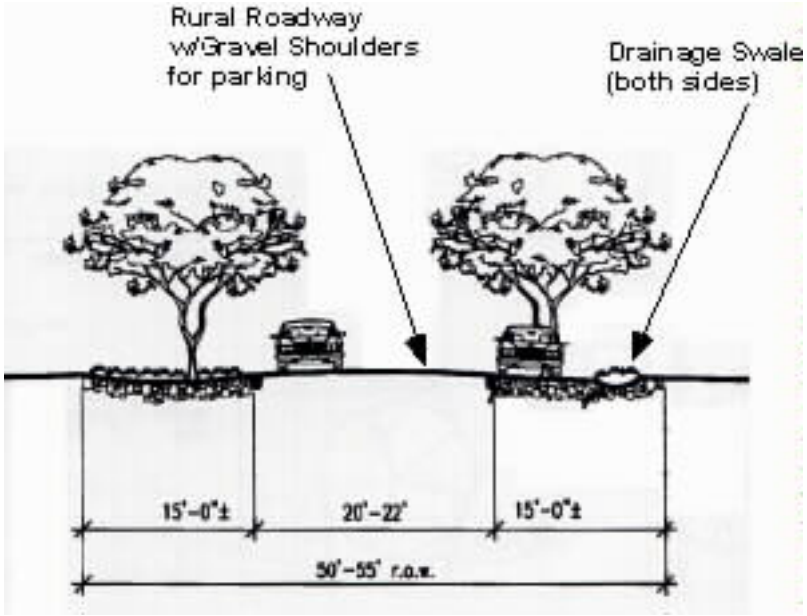
Rural Road Layout

Best Management Practices Fact Sheet

Project Description

Roads and other transportation related areas (parking lots, driveways, etc.) generally account for a majority of the impervious surface areas within a typical rural or suburban watershed. Therefore, reducing the overall impervious area associated with roads can be expected to pay dividends as far as reducing stormwater run-off volumes and peak flows. This action can significantly contribute to minimizing the negative impacts of stormwater run-off on downstream aquatic resources and help improve water quality. There are a variety of LID BMPs that can be utilized to accomplish this goal (Figure 1). These include the following:

1. Reduce street and roadway widths. A maximum width of 20–22 feet should be considered. Narrower road widths (15–18 feet) should be adequate for roads that carry only local or neighborhood traffic.
2. Utilize permeable surfaces for shoulders and parking areas.
3. Avoid the use of curb and gutter designs in favor of biofiltration swales (Figure 2) and filter strips to treat road run-off.
4. Utilize roadside vegetation, landscaping, or street trees to treat stormwater run-off (Figure 1).
5. Consider using alternatives to asphalt or concrete pavement for rural roads that do not carry high volumes of traffic (i.e., residential streets, access roads, etc.)



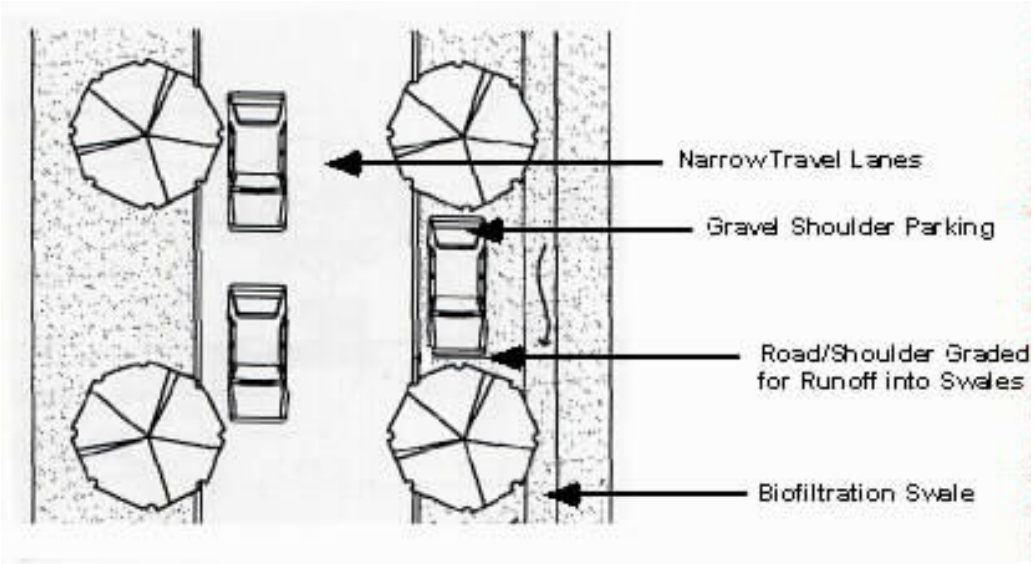


Figure 1. *Typical LID rural road layout*

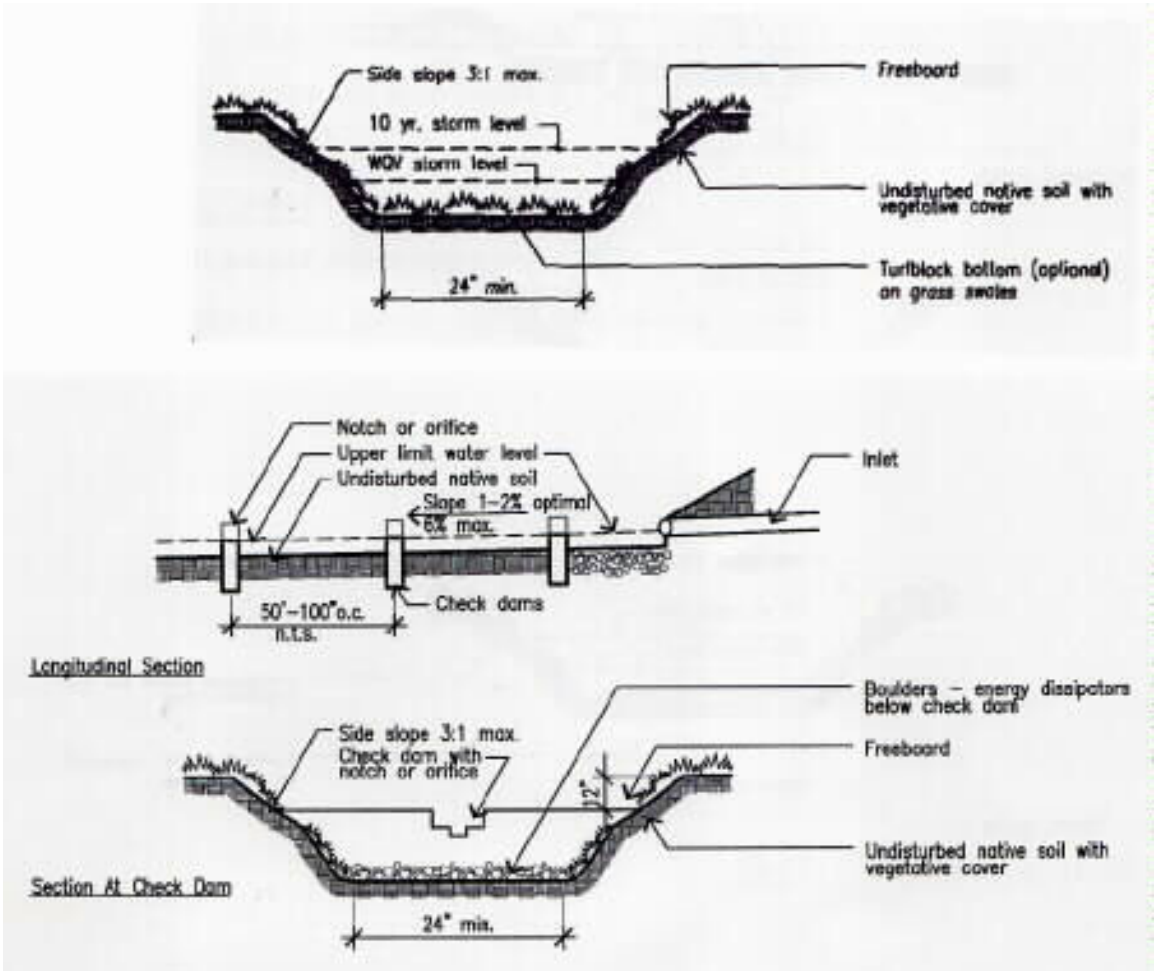


Figure 2. *Roadside biofiltration swale design*

Low Impact Development

Suburban and Urban Street Layout

Best Management Practices Fact Sheet

Project Description

Streets and other transportation related areas (highways, parking lots, driveways, etc.) generally account for a majority of the impervious surface areas within a typical urban or suburban watershed. Therefore, reducing the overall impervious area associated with roads can be expected to pay dividends as far as reducing stormwater run-off volumes and peak flows. This action can significantly contribute to minimizing the negative impacts of stormwater run-off on downstream aquatic resources and help improve water quality. There are a variety of LID BMPs that can be utilized to accomplish this goal (Figure 1). These include the following:

1. Reduce street and roadway widths. A maximum width of 28–30 feet should be considered. Narrower road widths (18–22 feet) should be adequate for roads that carry only local or neighborhood traffic.
2. Utilize permeable surfaces for shoulders and parking areas (Photo 1). Consider using alternatives to asphalt or concrete pavement for residential roads or alleyways that do not carry high volumes of traffic (i.e., neighborhood streets, access roads, etc.).
3. Avoid the use of curb and gutter designs in favor of biofiltration swales (Figures 2, 3, and 4) and filter strips to treat road run-off.
4. Utilize roadside vegetation, landscaping, or street trees to treat stormwater run-off (Figure 1).
5. Parking lots should also be targeted for LID retrofit. The use of permeable pavement/pavers, bioretention cells, and biofiltration swales are all potential methods for reducing stormwater run-off and improving water quality.

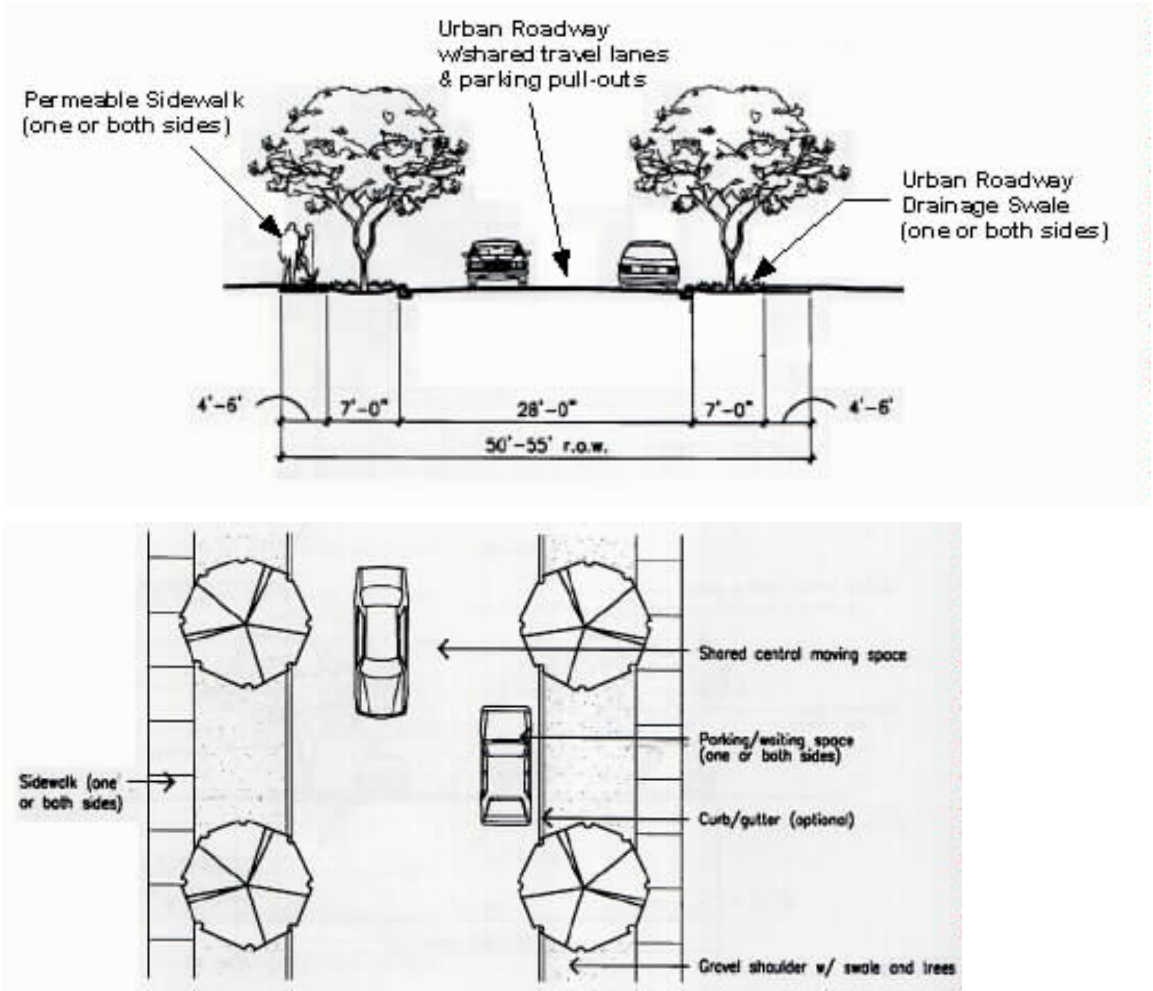


Figure 1. *Typical LID suburban-urban road layout*

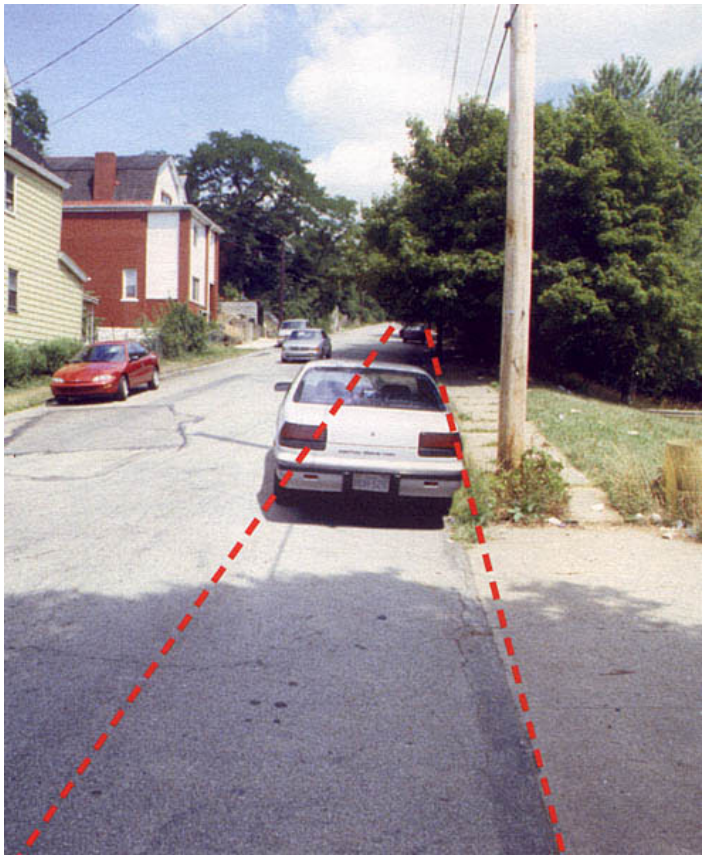


Photo 1. *Potential off-street parking area retrofit*

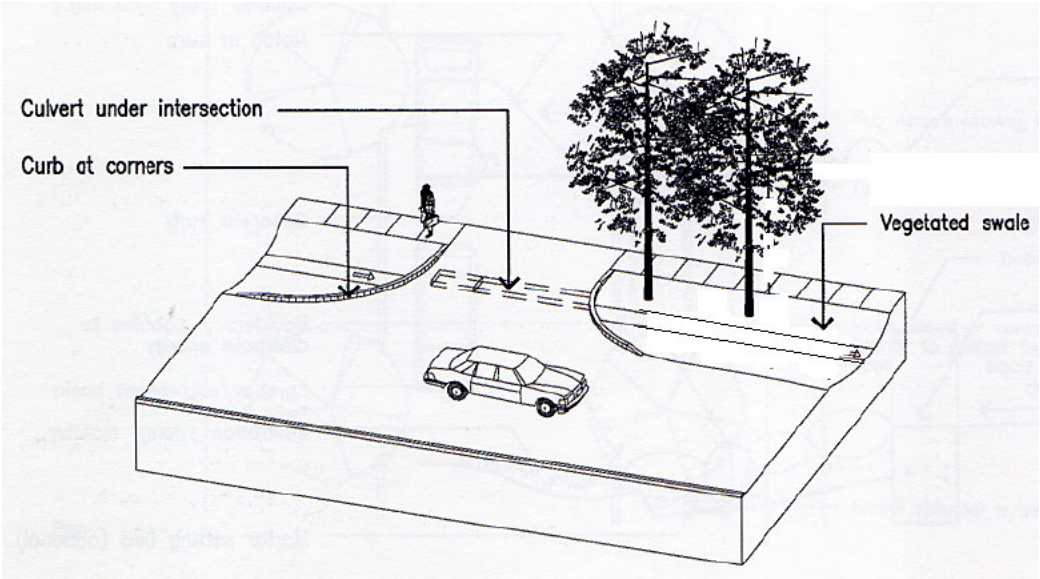


Figure 2. *Typical LID suburban-urban intersection*

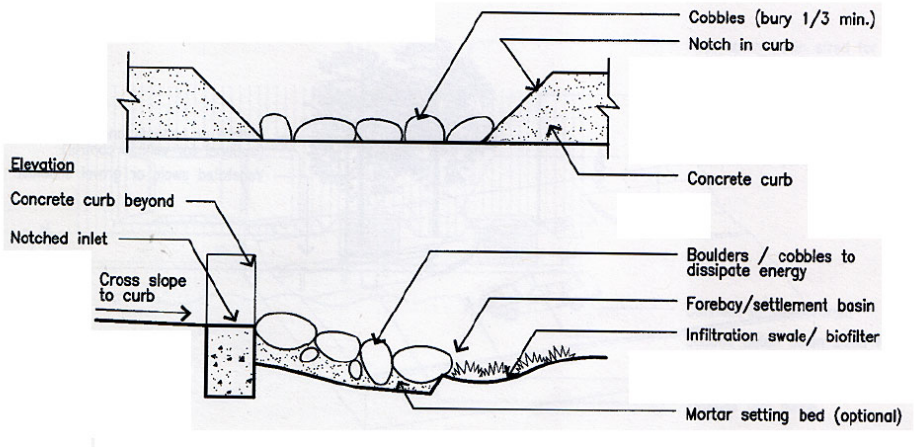


Figure 3. *LID suburban-urban roadside swale*

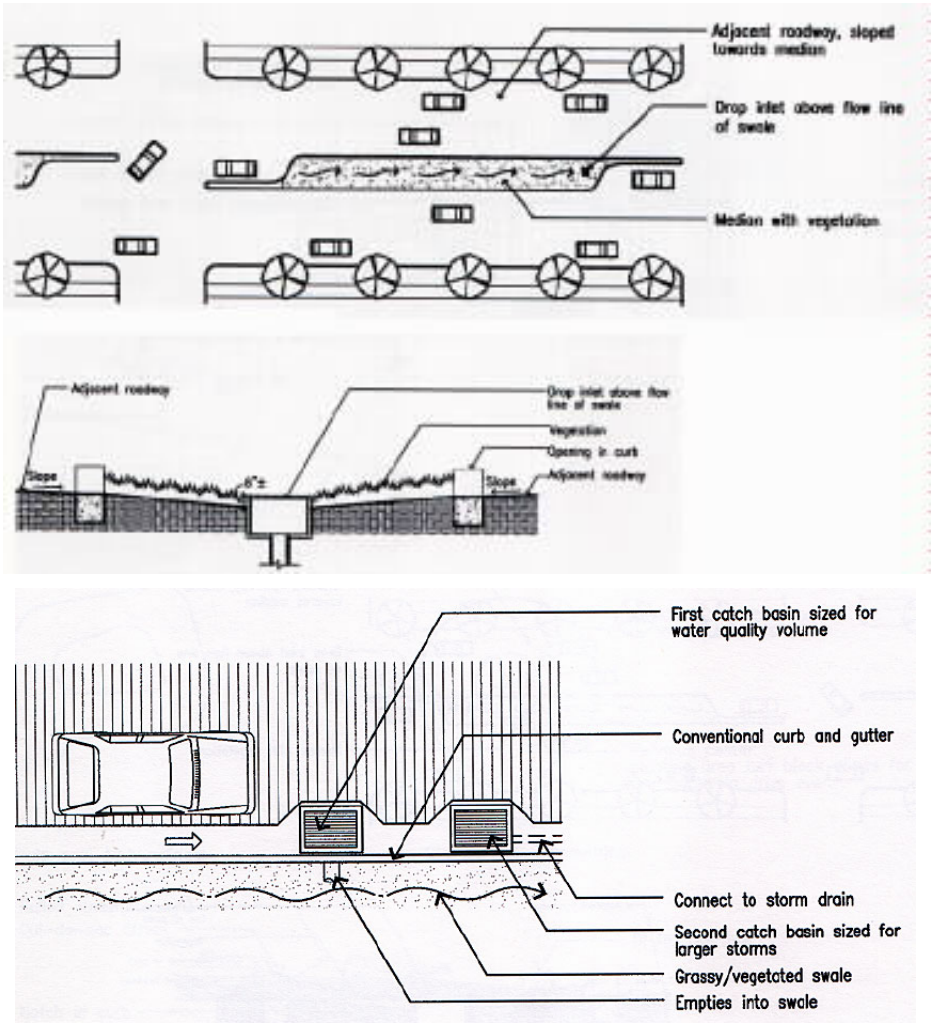


Figure 4. *LID suburban-urban road retrofits*

Low Impact Development

Urban and Urbanizing Watershed Retrofit

Best Management Practices Fact Sheet

1. **Impervious surface reduction** – A variety of methods are available to reduce overall watershed imperviousness or total impervious area (% TIA), and especially those impervious surfaces that are directly connected to the natural drainage network. The reduction of effective impervious area (% EIA) to near zero should be one of the primary watershed management goals. Narrow streets, shared driveways, and multi-level parking structures are examples of effective techniques for reducing imperviousness.
2. **Natural vegetation retention** – The conservation and restoration of natural forest and wetland cover should be a primary goal of a watershed management plan. Research throughout the country has demonstrated that natural vegetative cover is one of the most significant factors in maintaining natural hydrologic function within the watershed. Natural areas also have other benefits, such as wildlife habitat, recreational areas, and for aesthetics.
3. **Soil conservation and rehabilitation** – The impact of urbanization on natural soil structure and function can be quite significant. During the development process, the most absorbent upper soil layers tend to be removed during grading and/or compacted by heavy equipment such that the natural permeability of the soil is destroyed or reduced significantly. Aeration and soil amendment using organic matter can restore some of the natural storage and infiltration capacity, but the conservation of natural soils is the most effective tool available.
4. **Rainwater collection and re-use** – Roof run-off can be collected in rain barrels or cisterns and used for landscape and lawn irrigation. Roof drains can also be routed to landscaped or turf areas via underground infiltration systems. In general, these infiltration systems should not be placed over septic drain fields. In addition, some jurisdictions allow for the re-use of rainwater for flushing toilets as part of an integrated gray-waste re-use system within homes, offices, or businesses.
5. **Rooftop gardens or green roofs** – Large retail or office buildings have a significant rooftop impervious surface area component that could be reduced if the rooftop was vegetated. These "eco-roofs" are designed to capture rainfall from a specified storm event, treat it by biofiltration, and route the treated water to a water re-use system or to the stormwater network. A portion of the captured water will be returned to the atmosphere via evapo-transpiration and some will be retained within the rooftop vegetation. Green roofs also have energy savings benefits and can moderate building temperatures.
6. **Pervious pavement** – A wide variety of permeable pavers or porous surface treatments are available for use in walkways, patios, driveways, parking areas, and even roads with light traffic volumes. These techniques include concrete pavers, gravel-bed systems, and porous asphalt to name a few. Because, in typical urban watersheds, transportation-related impervious surfaces tend to make up a

large percentage of overall imperviousness, any increase in permeability of these hard surfaces can be a significant positive benefit.

7. **Disconnection of rooftops and paved areas** – Disconnection of downspouts, driveways, sidewalks, parking lots, and roads from the stormwater conveyance network is another option for dealing with water quality and run-off quantity problems. Routing of run-off from these impervious surfaces into infiltration systems, dry wells, bioretention cells, or biofiltration swales/strips can reduce overall run-off volume and significantly improve downstream water quality.

8. **Infiltration systems** – The construction of structural BMPs such as infiltration trenches or basins can be an effective method of reducing run-off while treating the stormwater and restoring some groundwater recharge capacity. Care should be taken in using infiltration such that untreated stormwater is not allowed to come in contact with drinking water aquifers. In most case, adequate pollutant removal is accomplished through a combination of biofiltration (running stormwater through vegetated swales or filter-strips) and percolation of stormwater through several layers of soil.

9. **Biofiltration and bioretention** – The use of vegetated BMPs to treat stormwater has been shown to be very effective for the removal of most common urban pollutants. Bioretention cells, bio-swales, vegetated roadside ditches, and biofiltration strips are all effective methods for water quality treatment and infiltration.

10. **Stormwater "hot-spot" treatment** – In some cases, especially in the ultra-urban environment, many of the LID techniques discussed above will not work because of space limitations or other site constraints. In these situations, priority must be given to treating the areas with the greatest pollution source potential. These sites are often referred to as stormwater "hot-spots". Ideally, source-control and "good housekeeping" measures should prevent the mixing of pollutants with stormwater and prevent the release of pollutants into receiving waters. However, it is strongly recommended that some type of structural BMP be installed if there is a potential for a toxic spill or pollutant release. There are several underground water quality treatment BMPs that are available for use in these situations (e.g., sand filters, drain-inlet inserts, or other filter devices).

Low impact development

Vehicle Fueling Stations

Best Management Practices Fact Sheet

Objectives

Vehicle fueling stations and maintenance facilities have specific design guidelines that are promulgated by the US EPA and state regulatory agencies. Designing for spill prevention is the initial step in the stormwater management (SWM) process. An emergency spill plan must also be developed and spill cleanup equipment staged on site.

The fueling area should be isolated from rainfall with a cover that extends at least 6 feet beyond the fueling area (see Figure 1). In addition, the fueling area must be such that any spills are contained within the fueling area and stormwater is prevented from running onto the fueling area. This is typically accomplished by grading the fueling area higher than the surrounding pavement and berming the fueling area to prevent run-on. A perimeter deck drain to capture spills and/or water tracked into the fueling area by vehicles also typically surrounds the fueling pad. This deck drain is normally routed to an oil-water separator or a sand filter for water quality treatment. The fueling islands should also be equipped with an emergency shut-off switch in case of a catastrophic spill.

The exact suite of BMPs that are applicable to a specific site will depend on the site layout (lot size, adjacent lots, street configuration, etc.) and characteristics (soils, gradient, forest area, etc.). Care should be taken to avoid using infiltration-based BMPs for treatment of any areas that may be prone to major fuel/oil spills. The overall goal is to integrate stormwater management into a functional site design.

LID Techniques

The following LID BMPs could be utilized at vehicle fueling stations:

- Rooftop and driveway run-off disconnection
- Biofiltration swales and filter-strips
- Forest retention or buffer
- Bioretention cells or “rain gardens”
- Rain barrels or cisterns
- Permeable pavement or pavers
- Infiltration trench or infiltration basin
- Landscape and garden soil amendment

BMP Operations and Maintenance

Property owner education is critical for the long-term success of LID stormwater BMP operations. Residents must understand the purpose of each BMP, how the individual BMPs fit into the overall site design, and how to optimize the performance of each BMP. In addition, basic maintenance must be clearly understood and carried out at the

prescribed frequency. Most LID techniques are relatively simple and require no special O&M procedures. Periodic inspections of each BMP during storm events and under non-storm conditions will normally detect any problems.

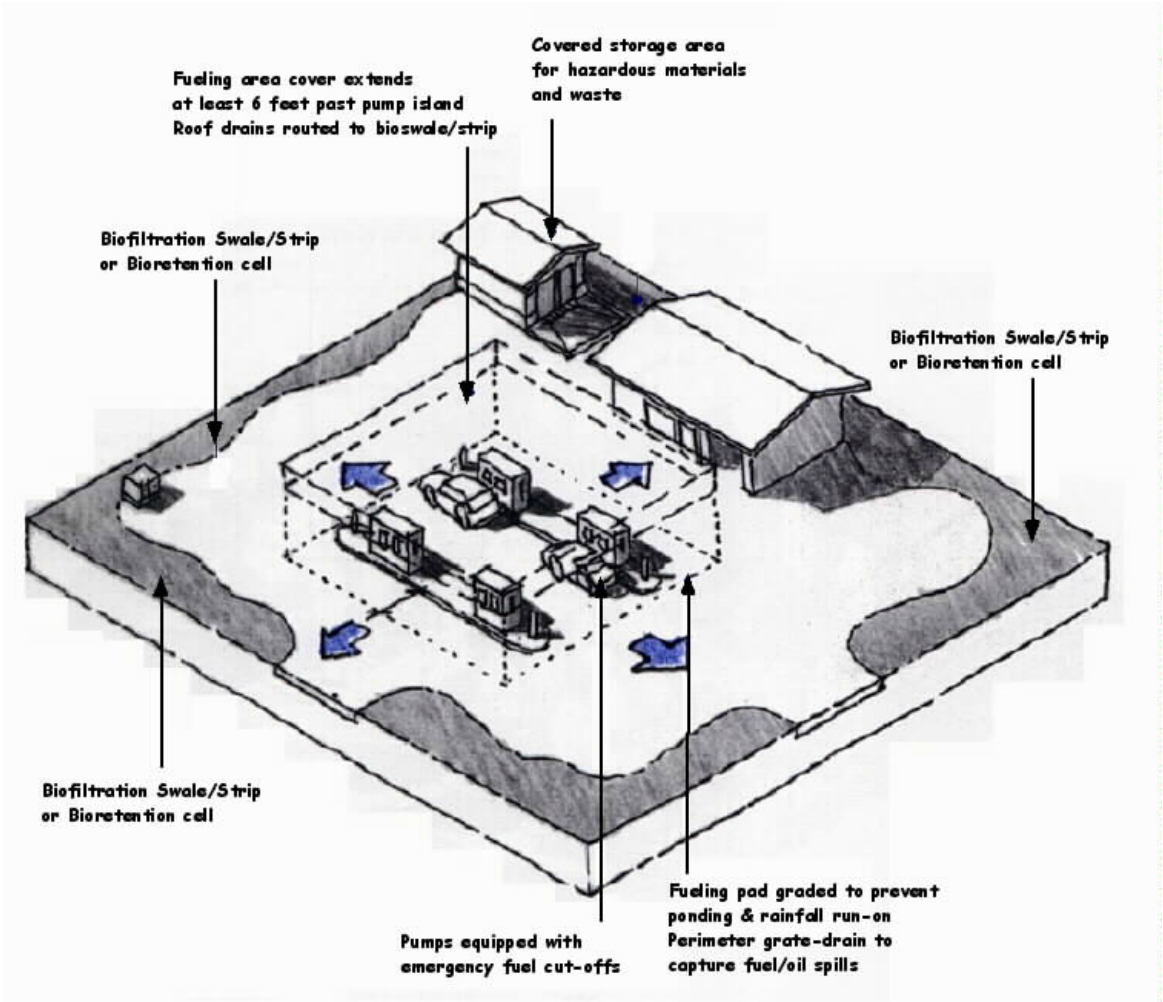


Figure 1. *Vehicle fueling station LID site layout, showing potential BMP applications (modified from* BASMAA*, 1999)*

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