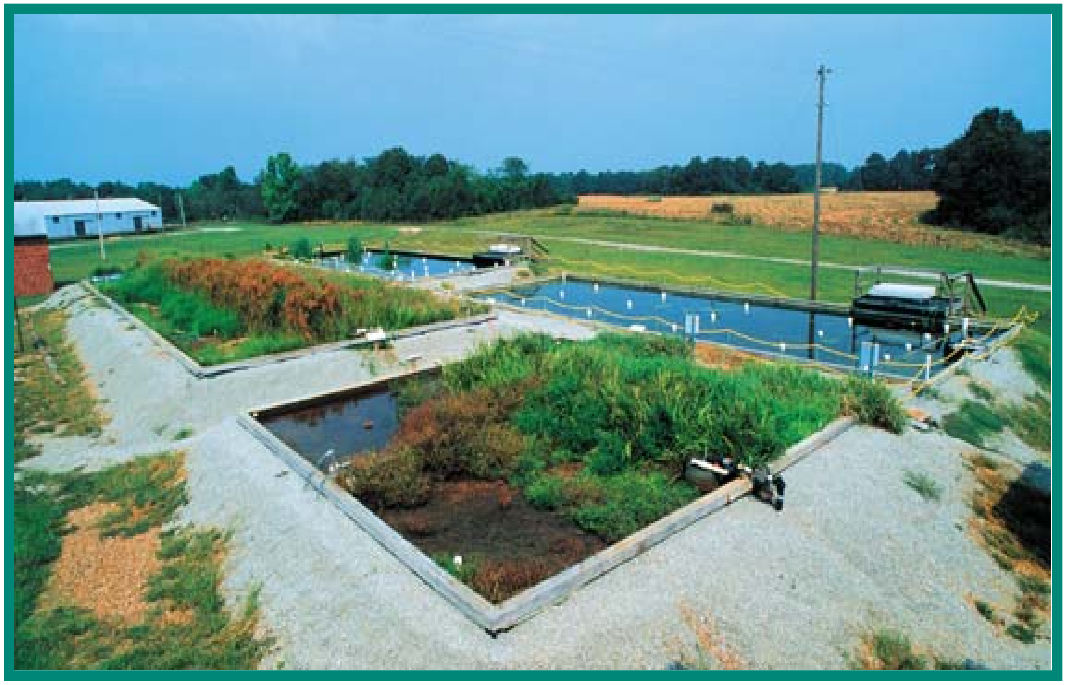
ESTCP
Cost and Performance Report

(CU-9520)



The Use of Constructed Wetlands to Phytoremediate Explosives-Contaminated Groundwater at the Milan Army Ammunition Plant, Milan, Tennessee

July 1999

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

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LIST OF ACRONYMS

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A2	The Aerobic Gravel-Based Demonstration Cell
AAP	Army Ammunition Plant
2A-DNT	2-Amino-4,6-dinitrotoluene
4A-DNT	4-Amino-2,6-dinitrotoluene
B1	The First Lagoon-Based Demonstration Cell
B2	The Second Lagoon-Based Demonstration Cell
BOD-55-Day	Biochemical Oxygen Demand
Ca	Calcium
Cd	Cadmium
CO2	Carbon Dioxide
Cu	Copper
2,6-DANT	2,6-Diamino-4-nitrotoluene
2,4-DANT	2,4-Diamino-6-nitrotoluene
1,3-DNB	1,3-Dinitrobenzene
DN-4,4-AZT	Dinitro-4,4'-azoxytoluene
3,5-DNA	3,5-Dinitroaniline
2,4-DNT	2,4-Dinitrotoluene
2,6-DNT	2,6-Dinitrotoluene
DoD	Department of Defense
ECWTP	Explosives-Contaminated Wastewater Treatment Plants
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
Fe	Iron
GAC	Granular Activated Carbon
GMF	Granular Media Filter
gpm	gallons per minute
HMX	Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine
L	Liters
L/min	liters per minute
MAAP	Milan Army Ammunition Plant
Mg	Magnesium

LIST OF ACRONYMS (continued)

min	Minute
Mn	Manganese
m-RDX	Mononitroso RDX
Ni	Nickel
NPDES	National Pollutant Discharge Elimination System
NPOC	Non-Purgeable Organic Carbon
Pb	Lead
ppb	parts per billion
R&D	Research and Development
RDX	Hexahydro-1,3,5-trinitro-1,3,5-triazine
TAT	Triaminotoluene
TN-2,2-AZT	Tetranitro-2,2'-azoxytoluene
TN-2,4-AZT	Tetranitro-2',4-azoxytoluene
TN-4,4-AZT	Tetranitro-4,4'-azoxytoluene
TNB	1,3,5-Trinitrobenzene
TNT	2,4,6-Trinitrotoluene
t-RDX	Trinitroso RDX
TVA	Tennessee Valley Authority
USAEC	U.S. Army Environmental Center
USEPA	United States Environmental Protection Agency
WES	Waterways Experiment Station
YSI	Yellow Spring Incorporated
Zn	Zinc

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ACKNOWLEDGMENTS

The Milan project was funded by the Department of Defense's Environmental Security Technology Certification Program (ESTCP) and executed under a partnering agreement among the United States Army Environmental Center (USAEC), the Tennessee Valley Authority (TVA), and the Waterways Experiment Station (WES). Relevant points of contact for each organization are provided in Appendix A.

Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

The groundwaters beneath many Army ammunition plants in the United States are contaminated with explosives. To help address this problem, the USAEC and TVA initiated a field demonstration program to evaluate the technical feasibility of using constructed wetlands for remediating explosives-contaminated groundwater. As part of this program, a field demonstration of constructed wetlands technology was conducted at the Milan Army Ammunition Plant (MAAP) near Milan, Tennessee (Figure 1). This demonstration's primary objective was to evaluate the technical feasibility of using wetlands for remediating explosives-contaminated groundwater. The goal of the Milan demonstration was to reduce TNT concentrations in MAAP's groundwater to levels less than 2 ppb and total nitrobody concentrations to less than 50 ppb. The term "total nitrobody" is defined here to mean the sum of the concentrations of the following explosives: 2,4,6-trinitrotoluene (TNT); Hexahydro-1,3,5-trinitro-1,3,5- triazine (RDX); Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX); 1,3,5-Trinitrobenzene (TNB); 2-Amino-4,6-dinitrotoluene (2A-DNT); and 4-Amino-2,6-dinitrotoluene (4A-DNT). Groundwater from two MAAP wells was used over the course of the demonstration. During the Phase II demonstration, the first well, MI-146, was used from the start of the demonstration on June 17, 1996, until November 21, 1996. The second well, MI-051, was used from November 21, 1996, until the end of the Phase III demonstration on July 21, 1998. Conversion to the second well was necessary due to falling explosive concentrations in the first well. The average total nitrobody and TNT concentration in the groundwater obtained from these wells is listed below.

	Phase II		Phase III
Chemical	**Well MI-146 From 6/17/96 to 11/21/96**	**Well MI-051 From 11/21/96 to 9/16/97**	**Well MI-051 From 9/16/97 to 7/21/98**
Total Nitrobodies	3,250 ppb	9,200 ppb	7,990 ppb
TNT	1,250 ppb	4,440 ppb	3,907 ppb

During the project, two types of wetlands were demonstrated: a gravel-based system and a lagoon-based system (Figure 2). Both the gravel- and lagoon-based systems were designed to retain the groundwater for approximately 10 days at an influent flow rate of 5 gpm per system. The gravel-based system consisted of two four-foot-deep, gravel-filled beds, cells A1 and A2, (Figure 3) connected in series and planted with emergent plants. The first gravel-based cell (cell A1) was maintained in an anaerobic condition by periodically adding a carbon source to the water. The second cell (cell A2) was maintained in an aerobic condition via a TVA-patented process (patent number 5,863,433). The lagoon-based system consisted of two two-foot-deep lagoons (cells B1 and B2) connected in series (Figure 3) and planted with submergent plants.

The demonstration results indicated that while both the gravel- and lagoon-based systems could remove explosives, the gravel-based system was clearly superior. The lagoon-based system met the goal of reducing TNT concentrations below 2 ppb only during the first 50 days of the demonstration and was unable to satisfactorily remove RDX and HMX or meet the total nitrobody-removal goals

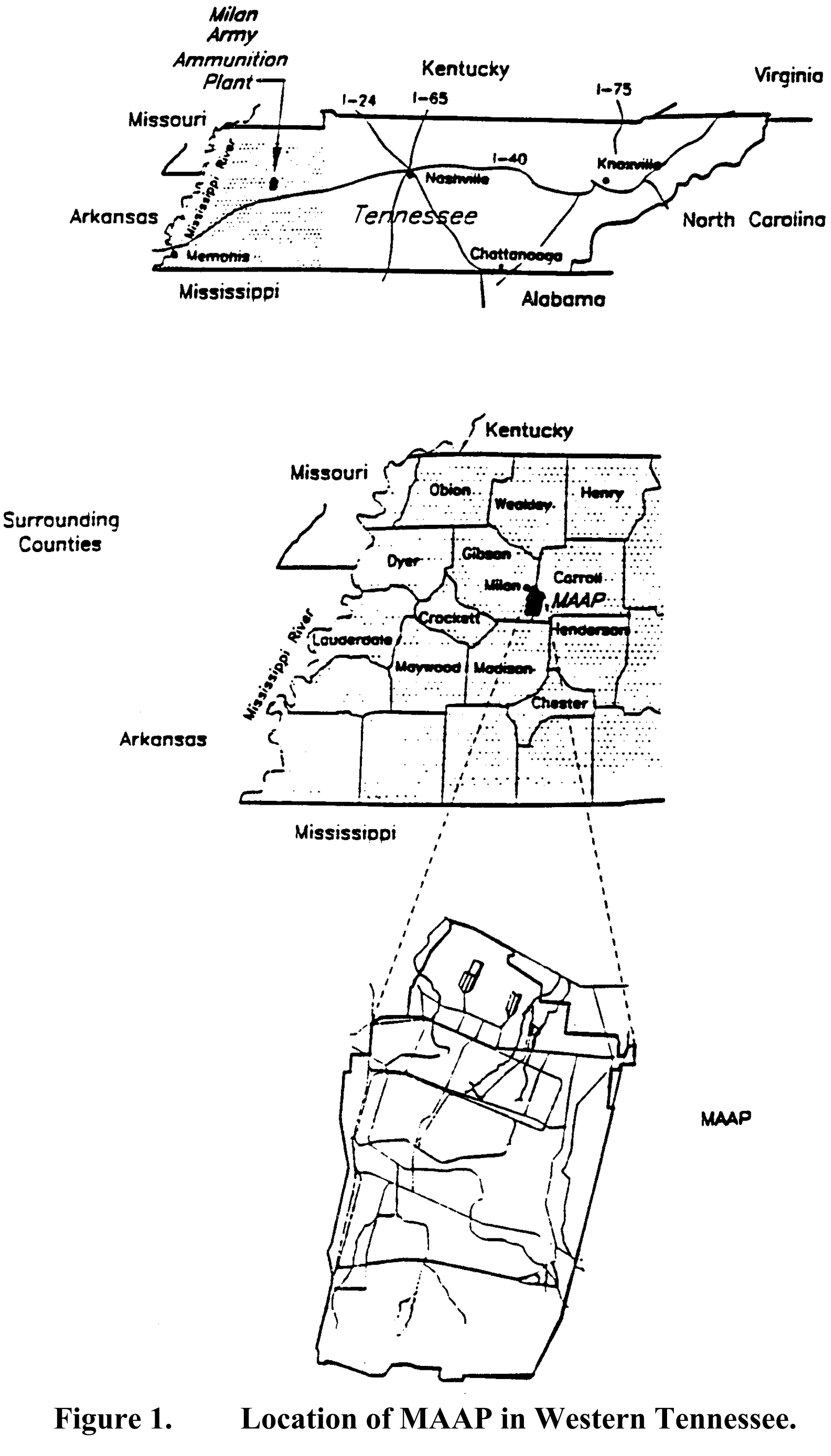

Figure 1. Location of MAAP in Western Tennessee.

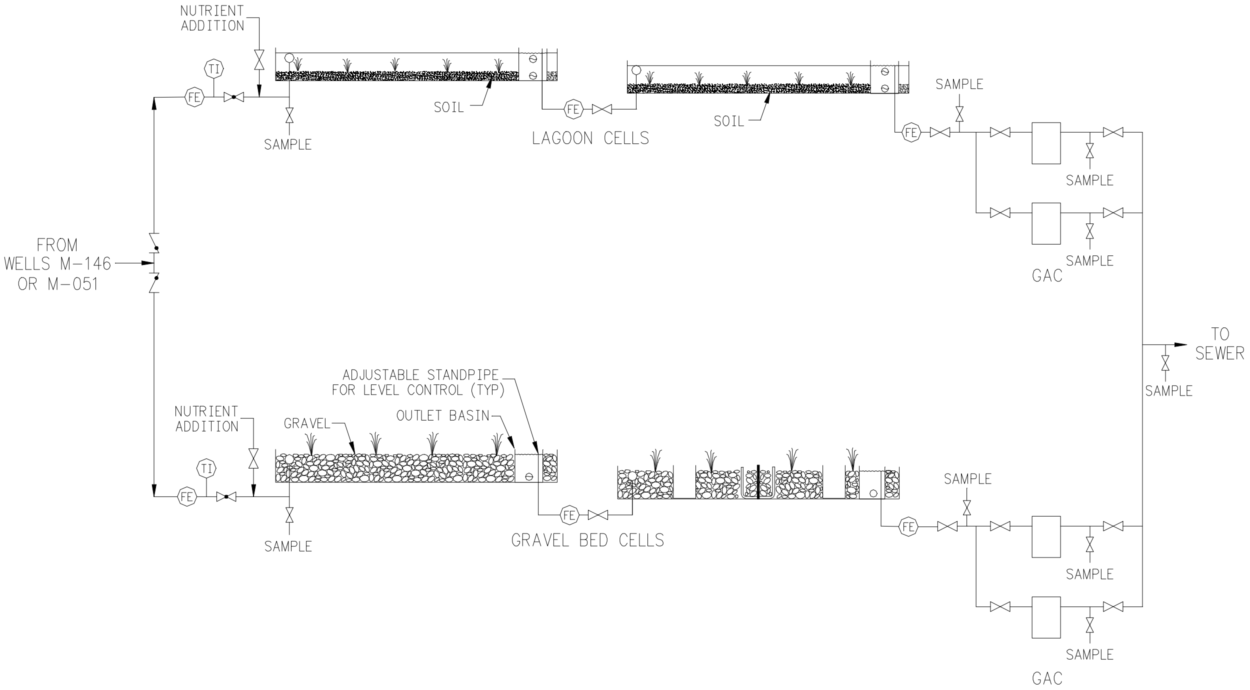

Figure 2. Wetlands Demonstration.

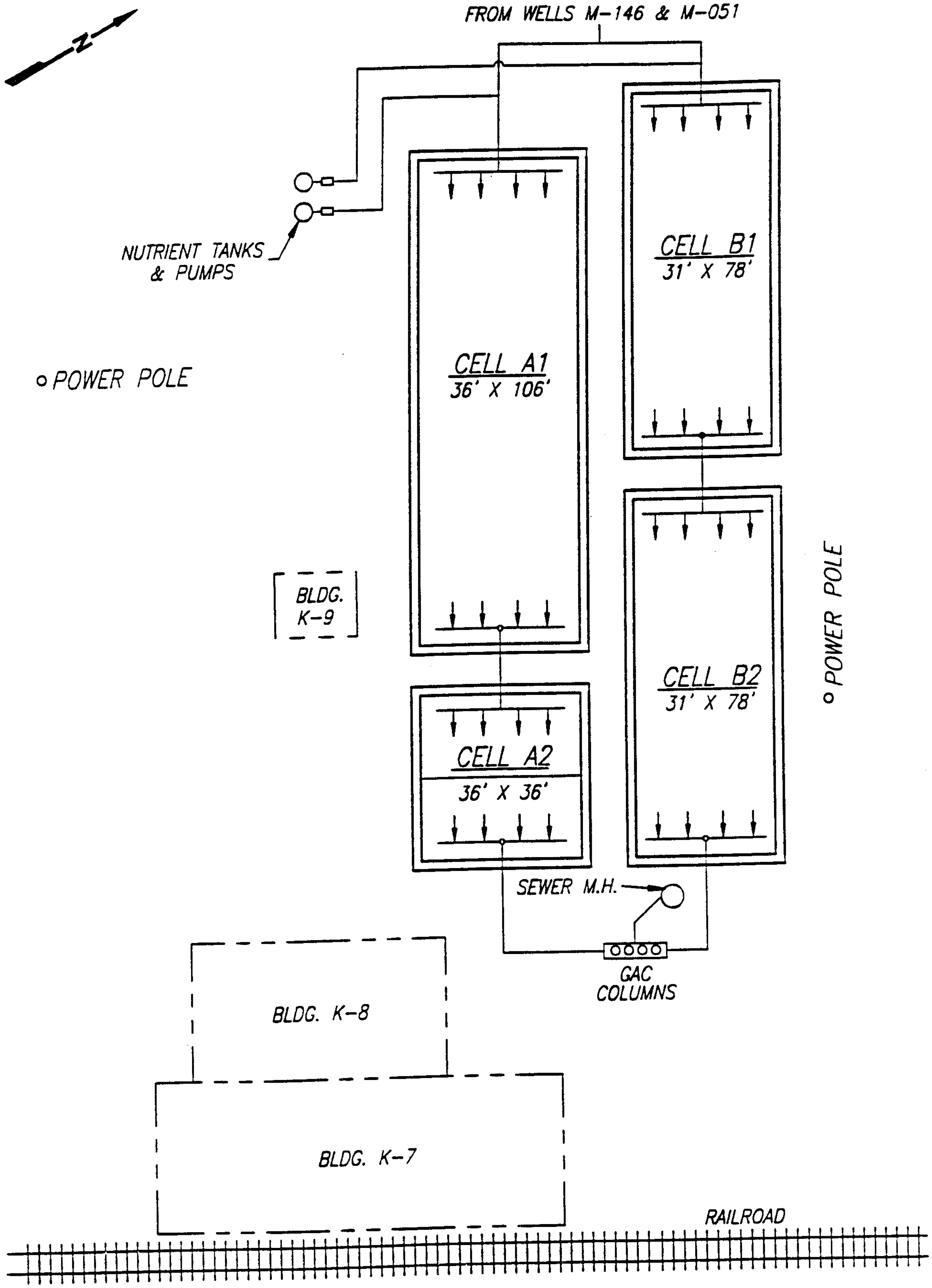

Figure 3. Site Plan for MAAP Demonstration.

during the demonstration. In addition, it was difficult to maintain an adequate plant population within the lagoon-based system. Problems encountered included:

- A severe tadpole infestation which severely defoliated the plants within two months of the initial 1996 planting.
- Difficulty in reestablishing plant growth due to photodegradation of explosives in the contaminated groundwater which inhibited photosynthesis by coloring the water a dark red.
- A June 1997 hailstorm which decimated parrotfeather, one of the few plants able to reestablish itself during the spring of 1997.

In contrast, the gravel-based system was able to degrade TNT, RDX, and HMX; was able to meet the demonstration goals during all but the coldest months; and was able to establish a sustainable ecosystem. During winter operations, the gravel-based system had difficulty meeting the total nitrobody reduction goal due to reduced microbial activity. Design and cost analysis indicate that a gravel-based system could be economically resized to overcome the winter performance issues.

To develop the cost analysis, cost data were developed based on a conceptual design for a 10-acre, full-scale, gravel-based system designed to treat 200 gpm of contaminated groundwater from B-line at MAAP. The estimated battery limits cost of constructing the 10-acre, gravel-based system was $3,466,000 in 1998 dollars. Assuming a 95% system availability and 30-year life, the total cost (operation and maintenance cost plus capital cost) for treating groundwater with the gravel-based system was estimated at $1.78 per thousand gallons of groundwater.

The results indicate that the gravel-based system is an economical and efficient alternative to remediate explosives-contaminated groundwater. The lagoon-based system's economic performance was not evaluated due to poor technical performance.

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2.0 TECHNOLOGY DESCRIPTION

Gravel-based wetlands are used for removing a broad range of contaminants from surface and groundwater sources. Degradation pathways in these systems are complex, but are generally based on the combined action of emergent aquatic plants and microbial populations composed of algae, bacteria, and fungi. Important parameters known to influence degradation pathways and kinetic degradation rates include:

- Temperature
- pH
- Dissolved oxygen concentration
- Redox potential
- Nutrient mix

Microorganisms are the primary source of various explosive-reducing enzymes in gravel-based wetlands.[Ref.1] Emergent plants also influence explosive reduction by producing nitroreductase enzymes. Explosives reduction occurs primarily in the anaerobic cell, which is fed a carbon source to promote anaerobic microbial activity. Explosive by-products, nutrients, and residual BOD-5 then enter the aerobic cell and are further reduced via aerobic microbial treatment.

The reduction pathways for each explosive vary. For TNT, enzymes reduce the nitro groups to amino groups. By-products observed to form during the demonstration were 2A-DNT, 4A-DNT, and 2,4-diamino-6-nitrotoluene (2,4-DANT).[Ref. 2] Further reduction may occur with formation of triaminotoluene (TAT), which has all of the nitro groups reduced to amino groups. The amino by-products can then polymerize to form harmless humic-like substances or the ring can be cleaved to produce aliphatic organic acids.[Ref. 3]

For RDX, the reduction of nitro groups to nitroso groups occurs via enzymatic activity, as well.[Refs. 2,4] RDX by-products observed during the demonstration were mononitroso RDX (m-RDX) and trinitroso RDX (t-RDX). These by-products undergo further degradation with ring cleavage occurring to form aliphatic organic acids and CO2. [Ref. 2]

The removal of HMX is suspected to occur under a mechanism similar to RDX where nitro groups are reduced to nitroso groups with further degradation occurring via ring cleavage.[Ref. 2]

To operate the gravel-based system, 5 gpm of contaminated groundwater was continuously pumped into the 0.088 acre anaerobic cell (cell A1) [Figure 3]. The contaminated water entering the gravel-based system took eight days to pass through the anaerobic cell, while microbial and plant enzymes in the anaerobic cell broke down the explosive-related contaminants. The water leaving the anaerobic cell was continuously discharged to the 0.030 acre aerobic cell through a header located at the discharge end of the anaerobic cell. The water was hydraulically retained in the aerobic cell for two days.

The aerobic cell was designed to remove explosive degradation by-products, biological oxygen demand, nutrients, and total suspended solids. The aerobic cell is a proprietary TVA design (patent number 5,863,433) which consists of two internal cells and a pumping system. Water leaving the aerobic cell was collected in a discharge header, pumped through drums containing granular activated carbon (GAC), and then flowed into the MAAP's sewer system. A GAC unit would not be used in a commercial wetland. The purpose of the GAC unit was to reduce total nitrobodies to below 50 ppb in the event the wetlands failed to perform, as expected, during the demonstration phase. The sewer led to the Wolf Creek Ordnance (WCOP) sewage treatment plant, having outfall 009. The sewage treatment plant's total nitrobody levels are limited to 70 ppb by MAAP's NPDES permit. Hence, the total nitrobodies in the water entering the sewage plant were below the NPDES permit requirement.

Four emergent plant species were grown on the surface of both of the four-foot-deep gravel beds: canary grass (*Phalaris arundinacea*), wool grass (*Scirpus cyperinus*), sweetflag (*Acorus calamus*), and Parrotfeather (*Myriophyllum aquaticum*). The canary grass, wool grass, and sweetflag were selected based on biomass-normalized kinetic constants for TNT and RDX removal. Their selection was also influenced by these plants' ability to supply carbon to the incoming water. Parrotfeather was included because it had been studied by the United States Environmental Protection Agency (USEPA) and others, and because it was both an emergent and submergent species and could be grown in both the lagoon- and gravel-based systems. In addition to adding the emergent plant species, the anaerobic cell was initially inoculated with commercially available forms of anaerobic bacteria (i.e., bacteria commonly used in household septic tanks).

Construction of the gravel-based system followed a protocol developed by TVA to build their Constructed Wetlands R&D Facility (see also Steiner and Watson, 1993[Ref. 5]). General design calculations for the systems were based on a total hydraulic retention time of 10 days and a minimum demonstration flow rate of 5 gpm (19 L/min to each system).

All cells were constructed aboveground using insulated four-foot-high, prefabricated, poly wall panels surrounded by earthen berms. Some excavation and earth moving was required to obtain the required depths and to provide backfill against the panels. All basins were lined with two layers of liner (20-mil, 12-ply, cross-grain, laminate polyethylene) to prevent seepage of contaminated water to the underlying soil. Geotextile mats were installed above and below each liner to prevent sharp rocks from penetrating each liner. The first liner held the basin contents. The second liner provided secondary containment and served as part of a leak-detection system. Three inches of gravel separated the first and second liners; the void space within the gravel matrix provided storage capacity for the leak detection system. The leak detection system for each cell consisted of the gravel catch basin, the secondary liner, and a standpipe for accessing the gravel basin.

The bottom of the gravel-based cells was located 18" below ground level. The earthen berms surrounding the gravel-based cells rose four feet above ground level. Nine inches of freeboard existed between the top of the berms and the gravel bed to retain rainwater entering the system.

Flow to the demonstration site was limited by the capacity of the original groundwater source (well MI-146). Based on pump tests, well MI-146 was expected to deliver 16 gpm. Consequently, the piping to each of the demonstration systems was designed to handle a maximum inflow of 8 gpm (30 L/min). This was done to allow for possible operation at shorter retention times. In the fall of 1996, the explosive concentrations in the water from well MI-146 began to decline. Consequently, this well was abandoned and water from well MI-051 was used.

Influent and effluent manifolds were installed on all of the wetland cells. Water entered the gravel-based cells (cells A1 and A2) through a distribution header located near the top of the cells (Figure 4), just below the surface of the gravel bed. Flow out of each cell was through a collection header located at the opposite end of the cell near the bottom. After reaching the collection header, the water flowed into a standpipe-based discharge system located in an outlet control sump near the end of the cell. Water in the A1 outlet control sump flowed into the inlet manifold of cell A2. Water discharged from the A2 outlet control sump flowed to granulated activated carbon (GAC) drums and was then discharged to the sewer. The activated carbon units were used for demonstration purposes only and would not be utilized in a full-scale system.

The water flow between the first and second cells was controlled by a gravity flow system based on the use of a standpipe (Figure 4). The water level in cell A1 was controlled by the height of a standpipe located in the outlet control sump.

Flow and level control through the aerobic cell (A2) were similar to that of the anaerobic cell (A1), described above, except the water was always discharged by a demand-type pumping system. The demand-type pumping system consisted of a submersible pump and a float-type level controller located at the bottom of the control sump (see location of control sump in Figure 4). The water level within the gravel-based cells was set approximately two inches below the surface of the gravel beds.

The gravel-based system's anaerobic cell was also equipped with a nutrient delivery system. The nutrients added were primarily carbon sources (milk starter or cane molasses syrup) although a small amount of nitrogen and phosphate were added during the second year of the demonstration. During the first year of the demonstration, 113.4 Kg of milk replacement starter (MRS) was added to the anaerobic once every two weeks. The MRS provided all the nutrients necessary to keep the system anaerobic. During the second year, one gallon of cane molasses syrup and 40 grams of diammonium phosphate were added to the anaerobic cell every day.

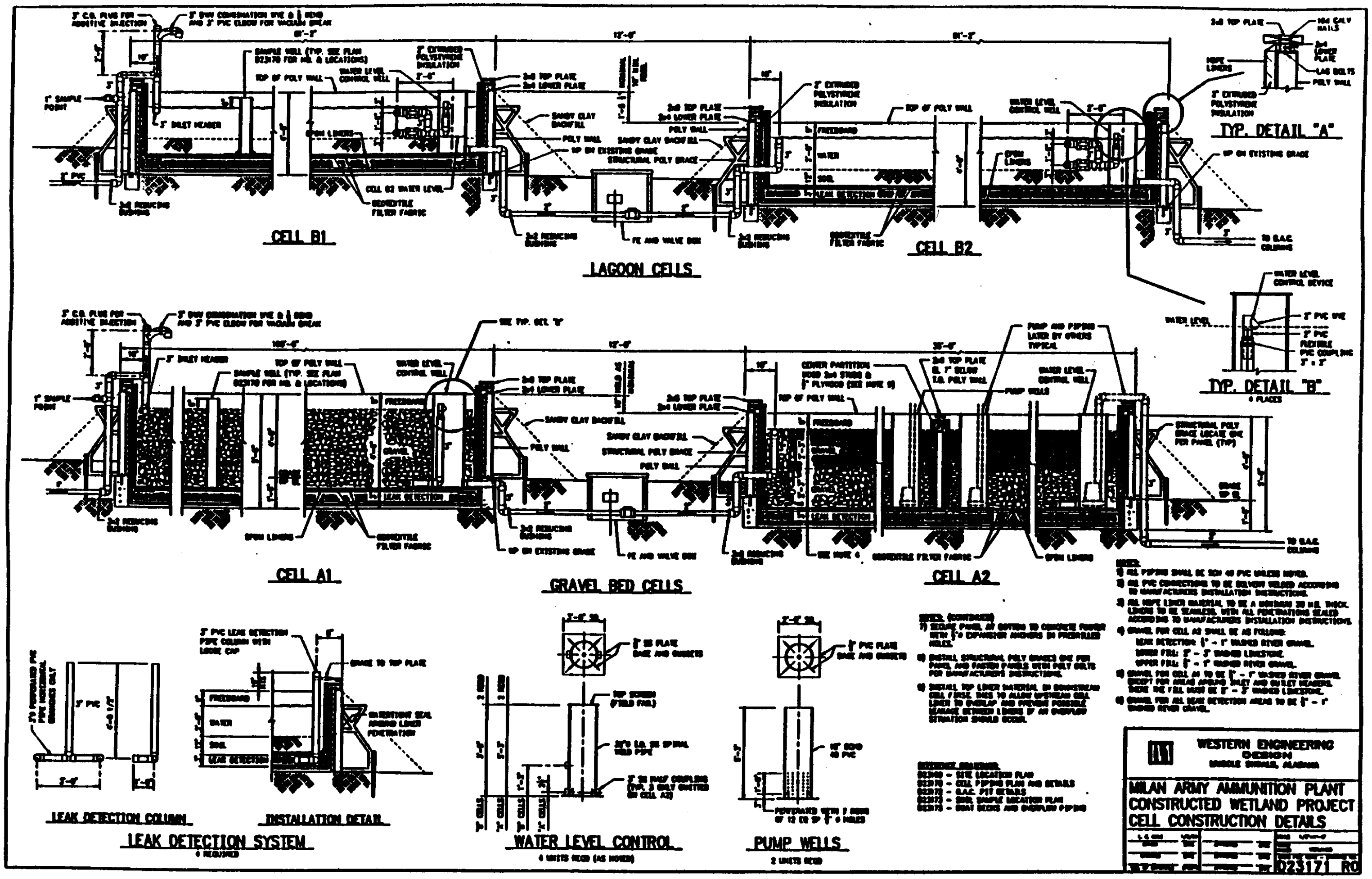


Figure 4. Cell Construction Details.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The primary performance objective was to demonstrate the remediation of groundwater such that the effluent:

- TNT concentrations were below 2 ppb
- Total nitrobody concentrations were below 50 ppb

The 50 ppb nitrobody limit was below the 70 ppb limit designated by MAAP's NPDES permit for the WCOP sewage water treatment plant.

Secondary goals were to produce effluent waters that would be acceptable for surface water discharge. Since BOD-5, pH, and total suspended solids analyses are commonly required in NPDES surface water discharge permits, these parameters were analyzed in effluent waters. In addition, by-products of explosive degradation, such as 2,6-DANT and 2,4-DANT, and the toxicity of effluent waters were analyzed to evaluate whether or not effluent waters would be safe for surface water discharge.

3.2 PHYSICAL SETUP AND OPERATION

This project was executed in three phases. During Phase I, plant screening studies and treatability studies were conducted to optimize the field design. While conducting these studies, standard methods were developed to evaluate the ability of aquatic macrophytes (large aquatic plants) to lower the contaminant levels of TNT, RDX, HMX, and related compounds in explosives-contaminated water. Then, a variety of submergent and emergent aquatic macrophytes were screened for their ability to remediate the contaminated water. Next, treatability studies were undertaken to test the performance of various wetland configurations.

During Phase II, the field demonstration systems were designed, constructed at MAAP, monitored for 16 months, and evaluated from both a technical and economic perspective. WES also conducted bench-scale tests with radiolabled TNT and RDX to determine the fate of explosives in aquatic and wetland plants during Phase II.[Ref. 6] Phase II began on June 17, 1996, when contaminated water was introduced into the gravel- and lagoon-based systems. The lagoon-based system operated on contaminated water through August 19, 1997, when the feed was switched to potable water for transition to a non-operational state. Contaminated water continued to be fed to the gravel-based system as part of the Phase III effort. Phase II sampling activities in the gravel-based system were continued through September 16, 1997.

During the course of Phase II, it became apparent that the gravel-based wetland's performance would be better than that of the lagoon and that acquiring additional data would be helpful. Areas of interest included:

- Continuing to establish the effect of long-term plant growth on explosive remediation.
- Continuing to examine nitrobody remediation at cold temperature.
- Examining the use of alternate carbon sources in the anaerobic cell (cell A1).

- Establishing the anaerobic cell's performance at a lower flow rate.
- Operating and maintaining the system in a manner similar to that required for a full-scale system.

These issues were addressed by extending the operating period of the existing demonstration program. This extension is referred to as Phase III. The Phase III program began on September 16, 1997, and was continued through July 21, 1998.

3.3 SAMPLING PROCEDURES

During Phase II, water, plant, gravel, and sediment samples were collected on a biweekly and bimonthly basis. Water samples were analyzed for the following:

- Explosives
- Explosive by-products
- Nutrients
- Dissolved oxygen
- pH
- Temperature
- Suspended solids
- Metals
- Chlorides
- Redox potential
- Electrical conductivity
- Chemical oxygen demand
- Biochemical oxygen demand

Intensive sampling was conducted every two months. During the intensive sampling periods:

- Additional water samples were collected to quantify explosive removal kinetics.
- Plant samples were collected to evaluate plant growth and assess the potential for explosive and explosive by-product accumulation.
- Sediment and gravel samples were collected to assess the potential for explosive and explosive by-product accumulation and toxicity to sediment invertebrates.
- Hydraulic tracer analyses were conducted to characterize water flow through the wetlands.

In addition, plant samples collected during one of the intensive sampling periods were sent to the WES to conduct bench-scale tests with radiolabeled TNT and RDX to determine the fate of explosives in aquatic and wetland plants.[Ref. 6] The water toxicity tests were conducted using fathead minnows (*Pimephales promelas*) and daphnids (*Ceriodaphnia dubia*). Sediment toxicity was evaluated using amphipods (*Hyalella azteca*) and midge (*Chironomus tentans*) larvae. Gravel toxicity was evaluated using amphipods (*Hyalella azteca*).

The water analysis consisted of screening tests to determine if the waters were toxic and follow-up tests were to be conducted if toxicity was found. The follow-up tests were designed to quantify the extent of the toxicity. Sediment toxicity tests were conducted to determine whether toxic substances were accumulating within the wetlands.

During Phase III, the routine water-sampling program was maintained, but was performed monthly as a means of monitoring system performance. The water-sampling portion of the intensive sampling program was also conducted monthly. However, the routine and intensive sampling programs were not conducted simultaneously, rather, these programs were conducted two weeks apart. A full description of the sampling procedures used during the demonstration program may be found in Reference 7.

3.4 ANALYTICAL PROCEDURES

A listing of the analytical procedures used during the demonstration program is provided in Table 1. A full description of the analytical procedures used may be found in Reference 7.

3.5 DEMONSTRATION SITE/FACILITY BACKGROUND

MAAP is a government-owned, contractor-operated military industrial installation under the jurisdiction of the Commanding General, Headquarters, United States Army Industrial Operations Command. The facility is operated by General Dynamics Ordnance Systems, Inc., and employs approximately 1,100 people. The original facility was constructed during World War II.

MAAP is located in western Tennessee straddling portions of Gibson and Carrol Counties (Figure 1). The city of Milan lies approximately one mile west; Humboldt lies 17 miles southwest; Trenton lies 18 miles northwest; and Jackson lies 28 miles south.

MAAP is located on 22,436 acres of land. Approximately 548 acres enclose various production lines; 7,930 acres are used as storage areas; and approximately 1,395 acres are used for administrative, shop maintenance, housing, recreation, and other functions. The wetland demonstration system was constructed in Area K adjacent to Building K-100 (see the plot of land designated as Area A just east of Building K-100 in Figure 5).

The available evidence suggests that the groundwater contamination at MAAP is related to discharges which occurred during the period between World War II and 1981. Before 1981, MAAP's production facilities discharged explosives-contaminated wastewater directly into open ditches that drained from sumps or surface impoundment into local streams. Several of these drainage ditches became contaminated with explosive residuals which leached into the groundwater. Once in the groundwater, the contaminants moved off-post to the north-northwest along the natural course of groundwater flow. In 1981, the direct discharges were discontinued and the installation production facility's wastewaters were redirected to newly constructed explosives-contaminated wastewater treatment plants (ECWTPs).

Discharges from the existing ECWTPs are not thought to have affected the groundwater because the discharge levels are low--about 20 parts per billion (ppb) total nitrobodies. In addition, it has been shown that the nitrobodies are not accumulating in the ditch's sediment or soils.

3.6 DEMONSTRATION SITE/FACILITY CHARACTERISTICS

The level of groundwater contamination at MAAP is extensive enough that a number of off-post areas may have been impacted. These areas include:

Table 1. Outline of the Intensive Bimonthly Sampling Plan (continued)

Table 1. Outline of the Intensive Bimonthly Sampling Plan

Parameters	Method[1]
Water Quality Parameters	
2,4,6-Trinitrotoluene (TNT)	AP-0062
Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX)	AP-0062
Trinitrobenzene (TNB)	AP-0062
Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX)	AP-0062
2,4-Dinitrotoluene (2,4-DNT)	AP-0062
2,6-Dinitrotoluene (2,6-DNT)	AP-0062
2-Amino-4,6-dinitrotoluene (2A-DNT)	AP-0062
4-Amino-2,6-dinitrotoluene (4A-DNT)	AP-0062
2,6-Diamino-4-nitrotoluene (2,6-DANT)	AP-0062
2,4-Diamino-6-nitrotoluene (2,4-DANT)	AP-0062
3,5-Dinitroaniline (3,5-DNA)	AP-0062
1,3-Dinitrobenzene (1,3-DNB)	AP-0062
Mononitroso RDX (m-RDX)	AP-0062
Trinitroso RDX (t-RDX)	AP-0062
Azoxy Compounds	
Tetranitro-2,2'-azoxytoluene (TN-2,2-AZT)	AP-0062
Tetranitro-2',4-azoxytoluene (TN-2,4-AZT)	AP-0062
Tetranitro-4,4'-azoxytoluene (TN-4,4-AZT)	AP-0062
Dinitro-4,4'-azoxytoluene (DN-4,4-AZT)	AP-0062
Environmental Monitoring	
Biochemical Oxygen Demand (BOD-5)	405.1 Series
Chemical Oxygen Demand	410 Series
Non-Purgeable Organic Carbon	415 Series
Ammonia Nitrogen	350 Series
Total Kjeldahl Nitrogen	351 Series
Nitrate & Nitrite Nitrogen	353 Series
Orthophosphate	SP-0060

Table 1. Outline of the Intensive Bimonthly Sampling Plan (continued)

Parameters	Method[1]
pH (lab samples)	150 Series
Dissolved Oxygen, pH, Temperature, Electrical Conductivity	Meter [2] (YSI sonde)
Oxidation Reduction Potential	Method 2580
Total Suspended Solids	160.2 Series
Chlorides	AP-0300
Metals (Ca, Mg, Fe, Mn, Cu, Ni, Zn, Pb, Cd)	200 Series
Toxicity Test With *Pimephales promelas* (Fathead Minnow)	EPA Method 1000.0 (Survival and Growth)
Toxicity Test With *Ceriodaphnia dubia* (Daphnid)	EPA Method 1002.0 (Survival and Reproduction)
Sediment Quality Parameters	
TNT	AP-0062
RDX	AP-0062
TNB	AP-0062
HMX	AP-0062
2,4-DNT	AP-0062
2,6-DNT	AP-0062
2A-DNT (TNT by-product)	AP-0062
4A-DNT (TNT by-product)	AP-0062
2,6-DANT (TNT by-product)	AP-0062
2,4-DANT (TNT by-product)	AP-0062
3,5-DNA (TNT by-product)	AP-0062
1,3-DNB (TNB by-product)	AP-0062
m-RDX (RDX by-product)	AP-0062
t-RDX (RDX by-product)	AP-0062
Azoxy Compounds	
TN-2,2-AZT	AP-0062
TN-2,4-AZT	AP-0062
TN-4,4-AZT	AP-0062
DN-4,4-AZT	AP-0062

Table 1. Outline of the Intensive Bimonthly Sampling Plan (continued)

Parameters	Method[1]
Toxicity Test With *Hyalella azteca* (Amphipods)	EPA Method 100.1 (Survival Test)
Toxicity Test With *Chironomus tentans* (Midge)	EPA Method 100.2 (Survival Test)
Explosives & Related By-Products in Plants	
TNT	AP-0062
RDX	AP-0062
TNB	AP-0062
HMX	AP-0062
2,4-DNT	AP-0062
2,6-DNT	AP-0062
2A-DNT (TNT by-product)	AP-0062
4A-DNT (TNT by-product)	AP-0062
2,6-DANT (TNT by-product)	AP-0062
2,4-DANT (TNT by-product)	AP-0062
3,5-DNA (TNT by-product)	AP-0062
1,3-DNB (TNB by-product)	AP-0062
m-RDX (RDX by-product)	AP-0062
t-RDX (RDX by-product)	AP-0062
Azoxy Compounds	
TN-2,2-AZT	AP-0062
TN-2,4-AZT	AP-0062
TN-4,4-AZT	AP-0062
DN-4,4-AZT	AP-0062
Hydraulic Tracer Analysis	
Bromide (Overall Mixing)	AP-0300
Bromide (Short-Circuiting)	AP-0300

[1] See Reference 7 for details on methods and procedures.

[2] Meter methods: pH method 150.1, dissolved oxygen method 360.1, temperature 170.1, and electrical conductivity method 120.1.

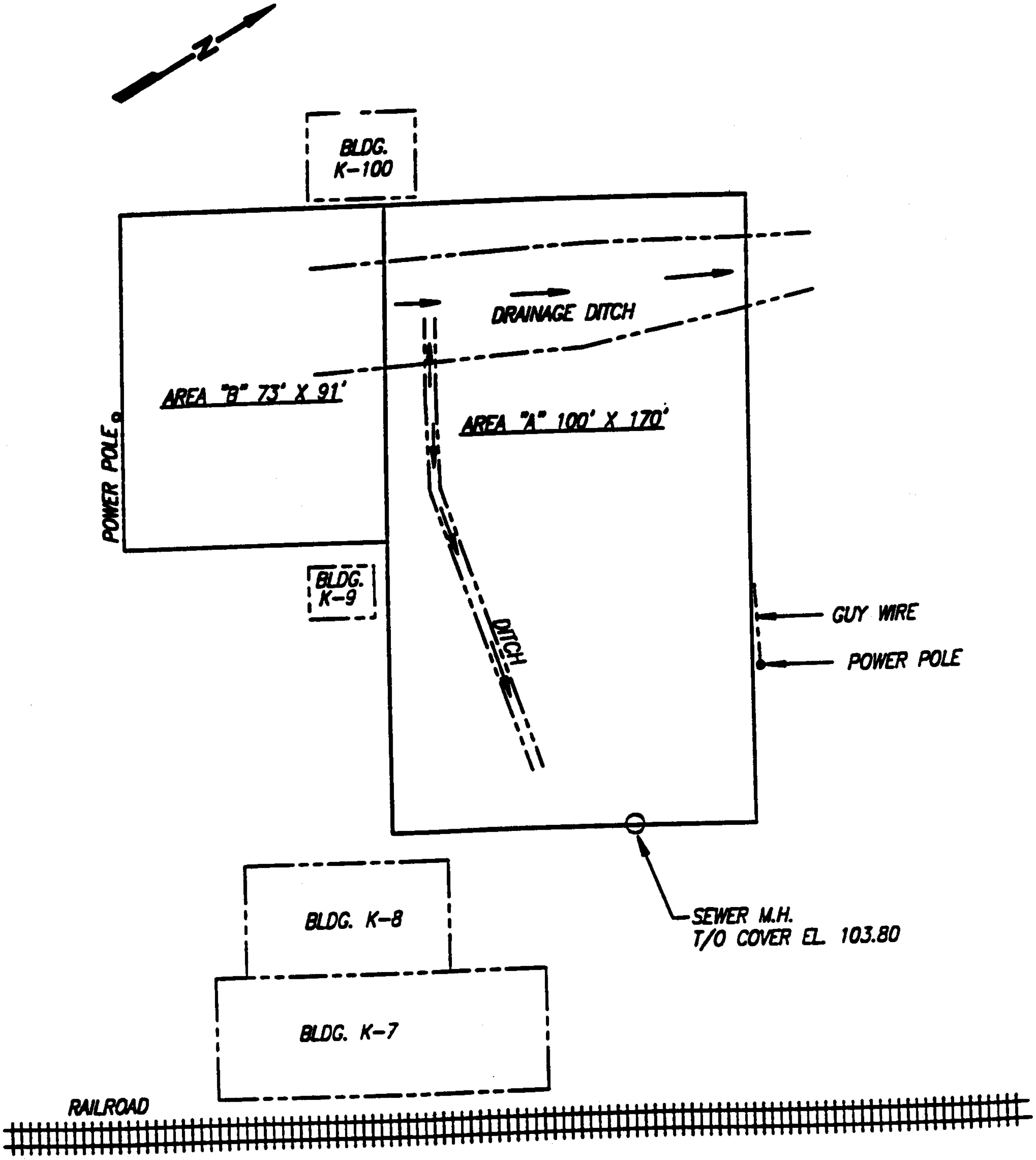


Figure 5. Milan Army Ammunition Plant Sites for Constructed Wetlands Demonstration for Remediating Explosives in Groundwater.

- Areas within the city of Milan
- An area between the installation and the city of Milan
- The area of Rutherford Fork, Obion River
- Residential wells
- University of Tennessee's Agricultural Station

The bulleted areas listed above are located near or adjacent to the off-post sites where contamination from explosive compounds has been detected.

Regular sampling of off-post residential wells, since 1982, indicates that contamination has been detected in residential wells at the Bledsoe residence and New Hope Church. Ditch D, located on-post, is the suspected source of this contamination. In early 1994, the Army detected RDX in two of the city of Milan's public water supply wells (wells 3 and 4) at levels below the USEPA health advisory level of 2 ppb during a monthly monitoring program. RDX concentrations exceeding a 2 ppb health advisory level were detected in city well 5. Subsequently, the well was shutdown. These wells are located northwest of the post within the city limits. Suspected source areas are Z line, which discharged to ditch D prior to 1981, and X line, which has discharged to ditch E prior to 1981.

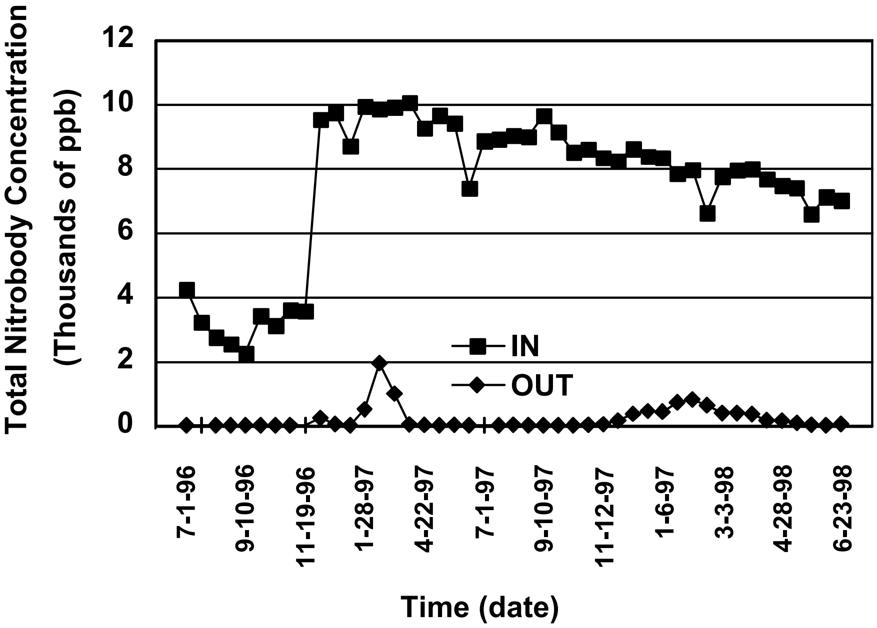
Groundwater from two MAAP wells was used over the course of the demonstration. During Phase II, the first well, MI-146, was used from the start of the demonstration on June 17, 1996, until November 21, 1996. The groundwater from this well had an average total nitrobody concentration of 3,250 ppb during Phase II. The second well, MI-051, was used from November 21, 1996, until the end of the Phase III demonstration on July 21, 1998. The groundwater from this well had an average nitrobody concentration of 9,200 ppb during Phase II (from November 1996 to August 1997) and averaged 7,990 ppb during Phase III. Conversion to the second well was necessary due to falling explosive concentrations in the first well. Average influent concentrations of explosives in the water from each well were as follows:

	Phase II		**Phase III**
Nitrobody or Explosive	**Well MI-146 From 6/17/96 to 11/21/96**	**Well MI-051 From 11/21/96 to 9/16/97**	**Well MI-051 From 9/16/97 to 7/21/98**
Total Nitrobodies	3,250 ppb	9,200 ppb	7,990 ppb
TNT	1,250 ppb	4,440 ppb	3,907 ppb
RDX	1,770 ppb	4,240 ppb	3,650 ppb
TNB	110 ppb	330 ppb	286 ppb
HMX	110 ppb	91 ppb	87 ppb

4.0 PERFORMANCE ASSESSMENT

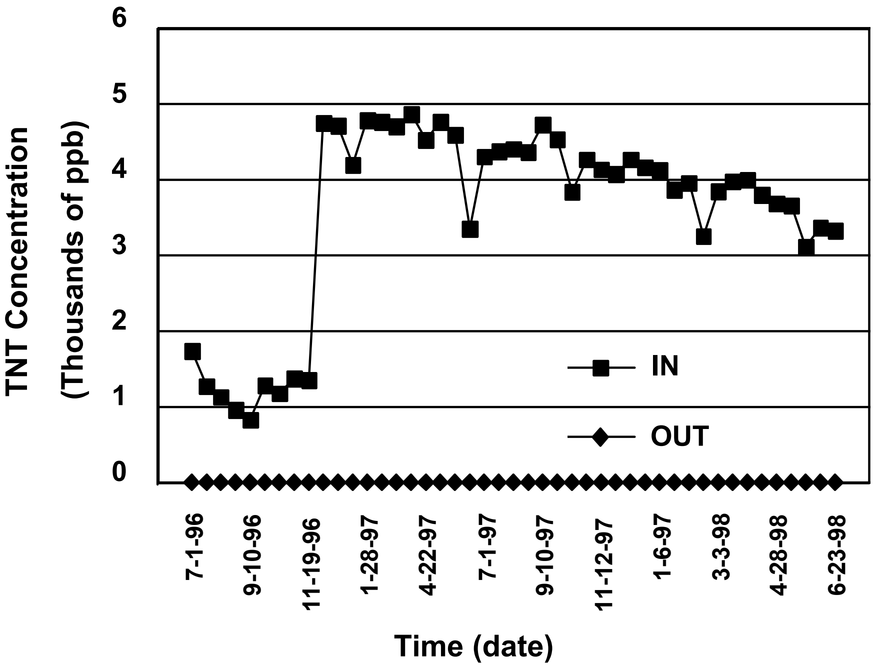
The demonstration results indicate the gravel-based system was able to degrade TNT, RDX, and HMX and was able meet the demonstration goals during all but the coldest months.[Ref. 7] The most significant effect of the cold weather was to limit the gravel-based system's ability to reduce the total nitrobodies concentration in the effluent below the 50 ppb demonstration goal (Figure 6). This was the direct result of a decrease in treatment efficiencies at low water temperatures. Cost analysis of the full-scale gravel-based system (Section V) indicated that the full-scale system could be economically resized to overcome these winter performance issues by increasing the water's retention time from a total of 10 days to a total of 14.5 days (12 days in the anaerobic cell and 2.5 days in the aerobic cell).

The goal of reducing TNT concentrations below 2 ppb was met during most of the demonstration (Figure 7). However, during the first year of operations, this performance measure was obscured by an instrument failure which increased the Method Detection Limit (MDL) for TNT from January 28, 1997, to March 19, 1997. The laboratory instrument failure caused the MDLs for TNT to rise from 2 ppb to 5 ppb. Although it is possible that the gravel based system was degrading TNT below the 2 ppb level during this period, it was not possible to document this as fact. The instrument problem was corrected and the problem did not reoccur. The TNT concentrations measured in gravel-based wetland's effluent were below the 2 ppb goal at all other times.



Note: When TNT was not detected the Method Detection Limit was plotted instead

Figure 6. Total Nitrobody Concentrations at the Inlet and Outlet of the Gravel-Based Wetland From June 17, 1996, to July 21, 1998.



Note: When TNT was not detected the Method Detection Limit was plotted instead

Figure 7. TNT Concentrations at the Inlet and Outlet of the Gravel-Based Wetland From June 17, 1996, to July 21, 1998.

5.0 COST ASSESSMENT

The cost assessment was developed based on a conceptual design for a 10-acre, full-scale, gravel-based system which had been designed to remediate 200 gpm of groundwater from MAAP's B-line. The overall design of the 10-acre full-scale system was similar to that developed for the demonstration system; however, some of the subsystems were altered to account for site differences and lessons learned during the MAAP demonstration. As indicated in Section IV, the primary modification was to increase the wetland's water retention time to 14.5 days as a means of meeting effluent standards in the winter. In addition, this system was designed to remove metal contaminants, as well as explosive contaminates, from groundwater. The full-scale system's conceptual design is described in Reference 7.

The estimated battery limits cost of constructing the 10-acre, full-scale, gravel-based wetland is $3,466,000 in 1998 dollars (Table 2). The battery limits cost includes all costs associated with constructing the wetland and should be considered a "turnkey" estimate. These costs include:

- Construction of the anaerobic and aerobic cells
- Planting of initial emergent macrophytes and seeding of microbes
- Installation of a carbon/nutrient feeding system
- All instrumentation needed to operate the facility
- An operating manual
- Electrical utility lines to 100 feet from the base of the wetland at the influent end
- 100 feet of 4-inch PVC line from the base of the wetland at the influent end (inlet for the contaminated water)
- 100 feet of 3.5-foot I.D. (minimum) culvert from the base of the discharge end of the wetland (discharge outlet for wetland)

The battery limits cost provided does not include:

- Groundwater extraction wells
- Utilities other than electricity (none expected)
- Post-construction sanitation facilities (none expected)
- Equipment for collecting and monitoring effluent (accounted for in operation and maintenance costs)
- Roads or parking lots
- Operator training

A total of nine months was allowed for design and construction of the wetland.

Estimated operation and maintenance costs are provided in Table 3. Assuming a 95% system availability and 30-year life, the total cost (operation and maintenance cost plus capital cost) for treating groundwater with this gravel-based system was estimated at $1.78 per thousand gallons of groundwater.

Since any present worth analysis of project-specific costs will require the insertion of other project-related costs, a breakdown in the format of a typical feasibility study is provided in Table 4. Table 4 was developed using the data from a June 1996 evaluation of Milan's 600 gpm GAC/GMF

Table 2. Estimated Battery Limits Cost for a Gravel-Based Wetland with Surface Water Discharge

	Battery Limits Cost, $
Direct Cost	
Excavation and Fill	$82,180[1]
Gravel Fill	$840,238[1]
Liner	$754,500[1]
Pumps	$12,115[1]
Tanks	$8,754[1]
Instruments	$28,079[1,2]
Insulation	$16,351[1]
Piping	$151,673[1]
Walls and Structures	$157,033[1]
Foundations	$52,886[1]
Electrical	$35,929[1]
Cleanup and Painting	$1,188[1]
Planting	$34,399[1]
Misc. (survey, soil tests, overheads, etc.)	$252,026[1]
Total Direct Cost	$2,427,349
Indirect Cost	
Additional System Cost	
Health and Safety	$12,474[3]
Bid Contingency, 15% of Direct Cost	$364,102[4]
Scope Contingency, 15% of Direct Cost	$364,102[4]
Subtotal	$740,679
Construction Subtotal (system cost + direct costs)	$3,168,027
Implementation Cost	
Engineering Services During Construction	$150,328[3]
Engineering & Design	$147,332[3]
Total Battery Limits Investment	**$3,465,687**

[1] Based on TVA assessment of a conceptual design of a commercial-scale facility.

[2] Includes the cost of sixteen oxygen meters for monitoring the anaerobic cell’s performance as well as other instrumentation.

[3] Based on TVA's assessment of actual needs for site construction.

[4] Used the same method outlined in previous U.S. Army Corps of Engineers' Focused Feasibility Studies.

Table 3. Operation and Maintenance Cost for a Gravel-Based Wetlands with Surface Water Discharge

Item	Annual Cost, $/year	Basis
Maintenance		
Berms	$4,000	$400 per acre * 10 acres[1]
Pumps	$485	4% of direct cost
Tanks	$350	4% of direct cost
Walls and Structures	$6,281	4% of direct cost
Pipes	$6,067	4% of direct cost
Electrical Equipment	$1,437	4% of direct cost
Instruments	$1,123	4% of direct cost
Total Maintenance	$19,743	
Raw Materials		
Carbon Source[2]	$14,334	357 lb/day * 365 day * $0.11/lb
Phosphate Source[2]	$1,200	$220/ton fertilizer * 5.45 ton/year
Electricity	$6,400	106,670 kWh per year * $0.06 per kWh[3]
Total Raw Materials	$21,934	
Subtotal Maintenance & Operations	**$41,677**	
Operator	$15,800	One $79,000/yr operator at 20%[3]
System Effluent Monitoring	$5,200	52 samples at $100 per sample[3,4]
Total O&M	**$62,677**	

[1] Rough cost from "Treatment of Wetlands" by Robert H. Kadlec and Robert L. Knight, 1996, page 607. Ref. 8

[2] Bioavailable carbon and nutrient sources provided to encourage anaerobic microbial activity.

[3] Cost from "Milan Army Ammunition Plant: Northern Boundary Groundwater Focused Feasibility Study," June 1996. Ref. 9

[4] Cost for obtaining one inlet and one outlet water sample and analyzing each sample for explosives each month. Other analytical cost associated with operating the system are included in the figures for capital cost, maintenance, and operating labor. This includes the cost of installing, monitoring, maintaining, and operating dissolved oxygen probes in the anaerobic cell.

Table 4. Present Worth Analysis on a 200 GPM Milan Wetland with Surface Water Discharge With Data From the Milan Army Ammunition Plant Northern Boundary Groundwater Focused Feasibility Study (June 1994)

!! NOTICE !!

THE DATA PRESENTED IN THIS TABLE IS GENERIC IN NATURE AND DOES NOT CONTAIN SITE-SPECIFIC DATA FROM MILAN'S ONGOING FEASIBILITY STUDY FOR B-LINE - MAAP'S FEASIBILITY STUDY COST MAY VARY FROM THAT PRESENTED HERE.

!! NOTICE !!

Item	Quantity	Capital Cost	Annual O&M	Present Worth of Annual Cost	
				20 year %5	**30 year 5%**
I. Administrative Actions					
1. Institutional Restrictions/Emergency Provisions		$25,000	$0	$0	$0
2. Public Education Program		$20,000	$0	$0	$0
3. Program Oversight (a)		$0	$75,000	$935,000	$1,153,000
Subtotal		$45,000	$75,000	$935,000	$1,153,000
II. General Actions/Site Preparation					
1. Parking/Staging Area/Access Roads		$34,291	$0	$0	$0
2. Treatment System Buildings (c)		$0	$0	$0	$0
3. Contractor Mobilization/Demobilization		$0	$0	$0	$0
Subtotal		$34,291	$0	$0	$0
III. Groundwater Treatment System					
1. Extraction Systems (e,f)		$56,805	$16,667	$208,000	$256,000
2. Wetlands Systems (g)		$2,427,349	$41,677	$519,000	$641,000
4. One Part-Time System Operators (h)	0.2@2080 hrs/yr.	$4,301	$15,800	$197,000	$243,000
Subtotal		$2,488,456	$74,144	$924,000	$1,140,000
IV. Discharge Systems(l)					
1. Piping System to Rutherford Fork		$95,678	$0	$0	$0
Subtotal		$95,678	$0	$0	$0
V. Long-Term Monitoring & Review					

Table 4. Present Worth Analysis on a 200 GPM Milan Wetland with Surface Water Discharge With Data From the Milan Army Ammunition Plant Northern Boundary Groundwater Focused Feasibility Study (June 1994) (continued)

Item	Quantity	Capital Cost	Annual O&M	Present Worth of Annual Cost	
				20 year %5	30 year 5%
1. Effluent Monitoring & Residuals Sampling		$3,117	$5,200	$65,000	$80,000
2. Quarterly Groundwater Monitoring and Reporting	20 wells * 200 gpm/600	$0	$33,667	$420,000	$518,000
3. Quarterly Surface Water Monitoring		$0	$0	$0	$0
4. Five-Year Review (15,000 ea.)	6 reports	$0	$3,000	$37,000	$46,000
Subtotal		$3,117	$41,867	$522,000	$644,000
SUBTOTAL (I, II, III, IV, and V)		$2,666,542	$191,010	$2,381,000	$2,937,000
ADDITIONAL SYSTEM COST					
1. Health and		$36,000	$0	$0	$0
2. Bid Contingency		$400,000	$0	$0	$0
3a. Scope		$400,000	$0	$0	$0
3b. Scope Contingency, 25% of Annual		$0	$48,000	$598,000	$738,000
Subtotal		$836,000	$48,000	$598,000	$738,000
CONSTRUCTION SUBTOTAL (I, II, III, IV, V, and		$3,502,542	$239,010	$2,979,000	$3,675,000
IMPLEMENTATION COST					
1. Engineering Services During		$201,000	NA	NA	NA
2. Engineering &		$182,000	NA	NA	NA
3. Permitting Coordination (a)		$0	NA	NA	NA
Subtotal		$383,000	NA	NA	NA
A. TOTAL CAPITAL COSTS		$3,885,542	NA	NA	NA
B. TOTAL ANNUAL COSTS		NA	$239,010	NA	NA
C. TOTAL PRESENT WORTH OF ANNUAL COSTS		NA	NA	$2,979,000	$3,675,000
TOTAL PRESENT WORTH OF CAPITAL AND ANNUAL COSTS				$6,864,542	$7,560,540

(a) Costs are the same as in the 1994 estimate for the GMF/GAC system. See Milan Army Ammunition Plant Northern Boundary Groundwater Focused Feasibility Study Table 7-2, page 7-

(b) Original capital cost converted to 1996 dollars using the CE index [i.e. new cost = original cost*

(c) Building included in wetland

(d) Included in capital cost for

(e) Original capital cost converted to 1996 dollars using the CE index and converted to a 200 gpm equivalent [i.e. new cost = original cost * (382.5/368.1) * (200

Table 4. Present Worth Analysis on a 200 GPM Milan Wetland with Surface Water Discharge With Data From the Milan Army Ammunition Plant Northern Boundary Groundwater Focused Feasibility Study (June 1994) (continued)

(f) Original O&M converted to a 200 gpm equivalent [i.e. new cost = original 600 gpm cost * (capital invest at 200 gpm/capital investment at
(g) From battery limits cost sheet (Table 3-
(h) One operator at 20% of his time. Operator cost based on $79,000/year per operator as per the original GMF/GAC
(i) Effluent Monitoring only, residual monitoring not
(j) Original O&M converted to a 200 gpm equivalent [i.e. ne w cost = original 600 gpm cost * (200 gpm/600

system. The example is intended to show how this estimate is likely to fit in a typical cost analysis and provides perspective of the total cost a facility might encounter. Table 4 is presented for informational purposes only and does not reflect actual costs allocated for any facility. Present worth was calculated on the basis of a 20-year life with a 5% discount rate. A 30-year life figure is included for informational purposes.

6.0 IMPLEMENTATION ISSUES

Although generally competitive with other remediation methods, a wetland's economic and technical feasibility is dependent upon site-specific factors including: regional temperature variations, rainfall patterns, groundwater flow characteristics, explosive type, explosive concentration, the presence of other contaminants, and other regulatory requirements. These factors can affect a wetland's configuration, size, performance, and cost. As a general rule, wetlands perform better in warmer climates with moderate levels of rainfall. Operational performance in colder climates is reduced. However, cost-competitive operation in less attractive climates is not out of the question.

Because of the complexity of these questions, it is generally advisable to consult with wetlands experts when attempting to determine economic and technical feasibility. The USAEC or TVA can provide assistance in this regard.

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APPENDIX A

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