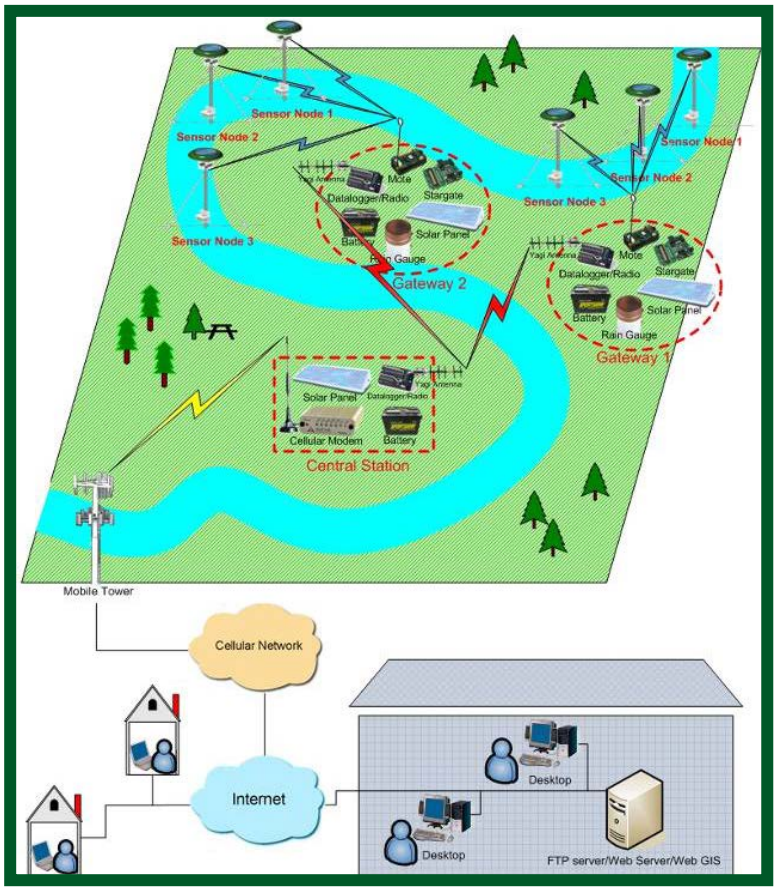
ESTCP
Cost and Performance Report

(RC-200817)



Continuous, Wireless Monitoring of Sediment Flux within Streams on Military Installations

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TECHNOLOGY CERTIFICATION PROGRAM

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COST & PERFORMANCE REPORT
Project: RC-200817

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ACRONYMS AND ABBREVIATIONS

ADCP	acoustic Doppler current profiler
AERTA	Army Environmental Requirements and Technology Assessments
APG	Aberdeen Proving Ground
ATC	Aberdeen Test Center
BMP	best management practice
BRAC	Base Realignment and Closure
EC	degrees Celsius
CNC	computer numerical control
CV	coefficient of variation
CWA	Clean Water Act
DLR	data loss rate
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
GPS	global positioning system
IR	infra-red
ISCO	in-situ chemical oxidation
km	kilometers
KSU	Kansas State University
LED	light emitting diode
LK	Little Kitten Creek
LRCN	long-range cellular network
LWSN	local wireless sensor network
m	meters
MATLAB	Matrix Laboratory
MBC	meteor burst communication
mg/L	milligrams per liter
MRSN	mid-range sensor network
MRWN	mid-range wireless network
m/s	meters per second
nm	nanometer
NPDES	National Pollutant Discharge Elimination System
NPS	non-point source

ACRONYMS AND ABBREVIATIONS (continued)

ORA	Orange
OSU	Oklahoma State University
PCB	printed circuit board
PNO	percentage of normal operation
PT	phototransistor
RMSE	root-mean-square error
RSSI	received signal strength indicator
SC	Silver Creek
SERDP	Strategic Environmental Research Development Program
SSC	suspended solids concentration
TMDL	total maximum daily load
TSS	total suspended solids
USEPA	U.S. Environmental Protection Agency
USGS	United States Geological Survey
V	volt
WB	Wildcat Bridge
WC	Wildcat Creek
WebGIS	Web-based Geographic Information System
WSN	wireless sensor network

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EXECUTIVE SUMMARY

Training activities on ranges are adversely impacting the environment. Vehicle traffic on unpaved roads and tank trails causes extensive erosion resulting in reduced water quality because of increased sediment loads. Currently, the Army does not have a way to continuously and directly monitor suspended solids concentration (SSC) in streams. In this demonstration project, twelve sensors that are designed to simultaneously measure SSC and flow velocity were deployed at three military installations – Fort Riley in Kansas, Fort Benning in Georgia, and Aberdeen Proving Ground (APG) in Maryland - through a three-tier wireless sensor network (WSN) to realize remote, Internet-based, continuous, long-term monitoring of sediment loads.

OBJECTIVES OF THE DEMONSTRATION

The objectives of the project included improvement of the sensor and the WSN, validating the accuracy, repeatability, and operability of the sensor in measuring SSC and flow velocity, and validating the functionality of the WSN.

TECHNOLOGY DESCRIPTION

The technology being demonstrated consists of two parts: 1) an optical sensor that continuously measures SSC in streams using visible and infrared (IR) lights and flow velocity using the cross-correlation method; and 2) a three-tier WSN to remotely transmit the SSC data from the sensor site(s) to the Internet. For the demonstration, 12 SSC/velocity sensors were deployed at three military installations – Fort Riley, Fort Benning, and APG, and a three-tier WSN was also deployed at these installations.

DEMONSTRATION RESULTS

Performance objectives of this project included accuracy and repeatability of the sensor in measuring sediment concentration and flow velocity; the operability of the sensor and its lens cleaning mechanism; and reliability of the components of a three-tier WSN examined through a long demonstration period.

The performance objectives for SSC measurement accuracy, repeatability, and operability were generally not achieved. The objective for SSC measurement accuracy was set to be ±10% or ±50 milligrams per liter (mg/L) of actual SSC, whichever is greater. Within the 95% confidence interval, the highest prediction error for the validation data set was found to be -46.2% for SSCs larger than 500 mg/L; and 290.9 mg/L for SSCs lower than 500 mg/L. The objectives for repeatability and operability was set to be one half of that for accuracy. The actually achieved repeatability was lower than 12.9% for SSCs larger than 500 mg/L, and lower than 292 mg/L for SSCs lower than 500 mg/L. Data post-processing applied to a six-month SSC data showed that the actually achieved operability was 23.1% for SSCs greater than 500 mg/L, and 234.5 mg/L for SSCs lower than 500 mg/L.

The performance objectives for flow velocity measurement were generally not achieved. The objective for measurement accuracy was set to be ±10% or ±0.01 meters per second (m/s) of

actual flow velocity, whichever is greater. The objective for repeatability was set to be one half of that for accuracy. The error found in velocity measurement was less than 27.8%. The repeatability for velocity measurement was lower than 0.37 m/s.

The performance objectives for various tiers and components of the three-tier WSN were generally not achieved. The objectives for percentage of normal operation (PNO) and data loss rates (DLR) for individual components in the network were set to be 90% and 0.5%, respectively. The lowest PNO and highest DLR recorded were 55% and 8.83%, respectively.

During the demonstration, one of the velocity sensors was deployed at a United States Geological Survey (USGS) stream-gaging station in Pine Knot Creek at Fort Benning. Through continuous velocity measurement over a one-year period, the measured point velocities were used to generate an index-rating curve that can be used to estimate the mean velocity from measured point velocity. The stage measurement provided by USGS and the estimated mean velocity were then used to estimate discharge using the "index-velocity method." This experiment demonstrated the possibility of using both stage and point velocity measurements to provide better discharge estimation.

IMPLEMENTATION ISSUES

Throughout the demonstration, SSC sensor calibration was found to be the most difficult issue for implementation. During the demonstration, a two-stage procedure was used for the calibration. The second stage of this procedure requires grab samples. In order to allow the sensor to measure SSC accurately within a wide range, a large amount of water samples with SSCs distributing within the desirable range need to be collected at the sensor site. This requires water samples to be taken during various rain events. The cost related to labor and transportation is very large.

In order to alleviate this concern, an alternative approach for the second stage of sensor calibration was developed since late 2011. The approach used a field sampler that continuously took water samples at various sediment concentrations and completes the sampling process within one to two hours. Detailed descriptions of this method are given in Appendix C of the Final Report.

Other implementation issues are related to deployment of the sensors in natural waters, including stream, lakes, rivers, and reservoirs. Securing the sensor in the water is always a challenge, especially during the high-flow season. Adding mechanical reinforcement usually alleviate the problem. However, for streams with sand/stone bottoms this may become extremely difficult.

The size of the stream needs to be considered when deploying the sensor. The general recommendation is that the sensor be deployed near a bank, perhaps within a distance of 20 feet. The maximum measurable SSC is 5000 mg/L, and the velocity sensor has a maximum measurable velocity of 5 m/s. These limits should not be exceeded.

1.0 INTRODUCTION

The purpose of this project was to demonstrate the following technologies: 1) a prototype suspended solids concentration (SSC) sensor that is insensitive to water color, sediment texture, and ambient light; 2) a flow-velocity measurement option on the SSC sensor; 3) a self-cleaning mechanism for sensor lenses to reduce the effect of biofouling; 4) a solar-powered, stand-alone wireless sensor node; and 5) a three-tier wireless sensor network (WSN) to connect distributed sensors to the Internet for web-based data accessibility and management.

1.1 BACKGROUND

Previous studies have indicated that training activities on ranges are adversely impacting the environment. For example, installations have many miles of unimproved roads and tank trails. Vehicle traffic on these roads and trails typically causes extensive erosion resulting in reduced water quality because of increased sediment loads. This is especially true at locations where an unimproved road or trail must traverse a stream or creek. Continued erosion can make trails impassable at crossing sites and result in environmental penalties for the installations. A projected increase in training activities and new construction at installations as a result of Base Realignment and Closure (BRAC) is expected to exacerbate the situation (Kunze and Jones, 2004).

The Army is addressing these problems with a variety of Best Management Practices (BMP) to control and minimize generation of sediment (Fabian, 2005). An inexpensive, long term SSC monitoring program is necessary to monitor the effectiveness of these BMPs. Currently, the Army does not have a way to continuously and directly monitor SSC in streams. Current standard practice is to use in situ turbidity measurements to estimate SSC, to perform automated monitoring with water samplers that are triggered during storm events, or to take grab samples. These methods are labor intensive and expensive, especially when sites are remote. Moreover, on-site water samplers or grab sampling can only provide intermittent measurements, often missing transient events when the potential for erosion is greatest. A WSN that contains multiple sensors with the ability to directly measure both SSC and flow velocity will better enable installation managers to remotely monitor sediment discharge at strategic locations on a continuous, long-term basis, thus helping installations comply with State and Federal Clean Water Act (CWA) and total maximum daily loads (TMDL) requirements. It will also help installation personnel more quickly identify potential sediment problems. The SSC sensors can be deployed in streams where water flows onto an installation, and thereby help quantify sediment flux onto installations during storm events. These data could identify off-installation suspended sediment sources. They can also be deployed in places where the Army has jurisdiction and sole responsibility for monitoring large water bodies, such as along the Chesapeake Bay.

Prior to this ESTCP project, the Kansas State University (KSU) team, as a part of the Strategic Environmental Research Development Program (SERDP) project SI-1339 (Assessing the Impact of Maneuver Training on Non-Point Source (NPS) Pollution and Water Quality, 2003-2006), developed a SSC optical sensor to continuously measure SSC in natural streams (Steichen et al., 2008). Details of this development are given in Section 2.1.2.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objective of this project was to demonstrate and validate the SSC/velocity sensor and the three-tier WSN for continuous, in situ, real-time measurement, and web-based, installation-scale monitoring of suspended sediment fluxes and sediment loads. The specific demonstration objectives included:

1. Add a stream flow-velocity measurement and a self-cleaning function to the SSC sensor through a simple structural expansion;
2. Develop a solar-powered, stand-alone, wireless sensor node mainly using off-the-shelf components to improve the field deployability;
3. Develop and deploy a three-layer WSN to enable installation-scale SSC/flow velocity monitoring;
4. Validate the accuracy of the sensor to measure SSC;
5. Validate the self-cleaning ability of the sensor;
6. Validate the ability of the sensor to measure flow;
7. Validate the functionality of the WSN for short and long range data transmission;
8. Validate the functionality of long-term, remote monitoring of sediment flux via the Internet and web-based geographical information system (WebGIS);
9. Demonstrate the applicability of this technology in military training land and in an estuarine tidal environment; and
10. Begin to transfer the technology by developing training tools and preparing the groundwork for disseminating the technology.

1.3 REGULATORY DRIVERS

The concern about suspended sediment in surface water stems from its adverse effects on aquatic plant and animal species. The Federal CWA was enacted by Congress to restore and maintain the health of surface waters. As required by the U.S. Environmental Protection Agency (EPA), the CWA developed water quality criteria, which established numerical maximum concentration levels for contaminants in discharges to surface waters. These criteria were used to develop regulatory requirements based on concentrations that will have an adverse impact on the qualities necessary for beneficial use of the surface waters. State and Federal CWA, and TMDL requirements have resulted in a need for this technology. Installations must comply with these State and Federal CWA and TMDL requirements. The CWA also created the National Pollutant Discharge Elimination System (NPDES) of permits that specified minimum water quality standards for discharged wastewaters and designates the types of pollutants to be regulated, including suspended sediments. Under the NPDES, point sources that discharge into waterways are required to obtain a permit for regulating their discharge. Each permit specifies effluent limitations for particular pollutants, and monitoring and reporting requirements.

Under Section 303(d) of the CWA and its implementing regulations, in addition to other pollutants, the CWA requires a TMDL for sediment be developed for those water bodies

identified as impaired by the state where technology-based and other controls will not provide for attainment of water quality standards. A TMDL is a determination of the amount of a pollutant from point, nonpoint, and natural background sources, including a margin of safety, which may be discharged to a water quality-limited water body. TMDL have been established to address impairments of water quality caused by sediment. In addition, point source sediment loads are regulated under the NPDES program.

Finally, the sensor and WSN technology also address Army Environmental Requirements and Technology Assessments (AERTA) A (2.5.e) for Sustainable Army Live-Fire Range Design and Maintenance. This is a priority user need for the Army. The technology applies to similar user needs of the other services. Applications include all areas where sediment monitoring must be performed for water quality compliance purposes.

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2.0 TECHNOLOGY/METHODOLOGY DESCRIPTION

Technology demonstrated in this project included an optical sensor to measure SSC and flow velocity and a three-tier WSN.

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

Detailed information on the sensor and the WSN are given in the following sections.

2.1.1 Overview of Sensor and Wireless Network Technology

The optical sensor developed prior to this project ("third generation" sensor design) consisted of a watertight enclosure with three light emitting diodes (LED) and four phototransistors (PT) mounted in a channel running the length of the underside of the enclosure. Inside the enclosure were electronic components that controlled the LEDs and measured the PT signals. Optical sensors worked on the principle that the LEDs generated lights peaking at different wavelengths, which were then transmitted through or scattered and backscattered by sediment in the path of the beam. The transmitted, scattered, and backscattered lights were measured by the PTs, which converted the light intensities to current signals that were representative of the SSC. The three feature wavelengths selected were: 1) 508 nanometers (nm) – blue-green; 2) 612 nm – orange; and 3) 768 nm – infrared (Stoll, 2004). For each LED, PTs were strategically placed at three angles from the incident light (180º, 90º, and 45º) to measure the transmitted, scattered, and backscattered lights, respectively.

Individual sensor nodes were deployed as part of a three–tier WSN to enable continuous, long-range SSC data transmission. The three-tier wireless communication network consisted of multiple local WSN (LWSN), a mid-range wireless network (MRWN), and a long-range cellular network (LRCN) (Figure 1).

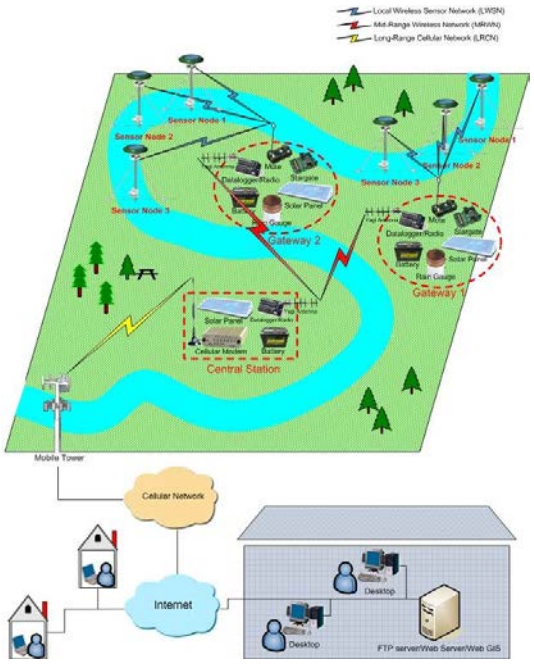

Figure 1. A figurative view of a three-tier wireless sensor network.

2.1.2 Chronological Summary of the Development of the Technology Prior to this Project

The SSC optical sensor ("first generation" design) was originally developed at KSU as part of SERDP project SI-1339 (Assessing the Impact of Maneuver Training on NPS Pollution and Water Quality, 2003-2006) (Steichen et al., 2008). In 2006, prototype SSC sensors ("second generation" design) and WSN were installed and tested at several sites in Kansas and at a low water stream crossing site on Upatoi Creek at Fort Benning, GA (Zhang et al., 2007; Han et al., 2007, Zhang, 2009).

Several sensors and a two-tier WSN were installed at Little Kitten Creek in Manhattan, KS, in August 2006. The two-tier network was similar to the three-tier WSN, except that it contained only two network tiers – a LWSN and a LRCN. In August 2007, two SSC sensors and a similar, two-tier wireless sensor network were deployed in an urban area of Kansas City as a part of a project on "Stormwater BMP Evaluation and Design" (Han et al., 2007).

In a joint effort between KSU and Aberdeen Test Center (ATC), four SSC sensors ("second generation" design) were installed in June 2006 at a low water stream crossing at Fort Benning, GA, where they successfully monitored SSC at the low water stream crossing for eight months, with SSC being continuously monitored at 1-minute intervals. This demonstration identified several issues related to deployment of the SSC sensor nodes at remote sites on Army training ranges. The most important issue was clogging and biofouling on optical lenses. A post-processing algorithm using Matrix Laboratory (MATLAB) software was developed and implemented to correct the effects of clogging and biofouling on SSC data. The demonstration at Fort Benning also allowed comparisons between different designs of the SSC sensor. An open-bottom design proved to be the least susceptible to lens clogging and biofouling (Zhang et al., 2007, Zhang, 2009). Based on these findings, the "third-generation" sensor was designed.

2.1.3 Development Conducted Under the ESTCP Project

Development conducted under the ESTCP project included modification of the sensor, the addition of a self-cleaning mechanism to the sensor, and hardware and software development for the WSN as discussed in the following sections.

2.1.3.1 <u>Sensor Modification – The Fourth Generation Design</u>

The SSC sensors being prepared for the ESTCP demonstration ("fourth generation" design) used a new design that was a modification based on findings and lessons learned during the earlier experiments. Several modifications were made on the sensor: 1) a new case design that allowed air-blast cleaning and velocity measurement; and 2) a printed circuit board (PCB) for sensor signal conditioning, processing and control. The PCB also interfaced with a thermocouple to continuously monitor water temperature and a rain gauge to monitor precipitation. With these modifications, data packets including measured SSC, flow velocity, water temperature and precipitation were transmitted to the WSN at programmable time intervals.

The optical SSC sensors designed in 2005 ("third generation") were fabricated manually using an aluminum case (Figure 2a). In 2008, a new design ("fourth generation") was developed in collaboration with the KSU Advanced Manufacturing Institute. The new design used an acetal

case (Figure 2b). The sensor body was manufactured on a Computer Numerical Control (CNC) turning center.

(a) **(b)**

Figure 2. Sensor designs (a) "third generation" (2005), (b) "fourth generation" (2008).

The LEDs and four PTs mounted in a channel running the length of the underside of the enclosure can be seen in Figure 3.

Figure 3. Side (left) and bottom (right) views of the Optical Sensor.
Note the channel on the bottom of the sensor enclosure.

The velocity measuring function was added to the SSC sensor by a simple structural modification – adding a ring of "Downstream Orange LED" as shown in Figure 4. The "downstream LED" ring was placed 4 centimeters (cm) from the "Upstream LED" ring. With this known distance, flow velocity can be calculated from the time the flow traveled from the "upstream" to the "downstream" ring, which can be estimated from the signals measured at the PTs in the two rings using the cross-correlation method (Dvorak, 2012).

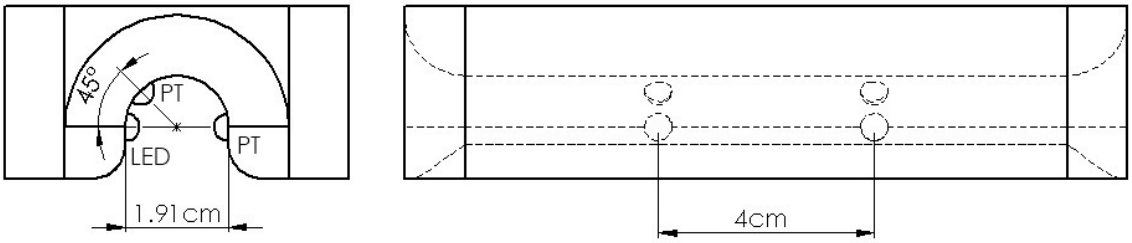

Figure 4. Orange LED and PT arrangement in the sensor.
(infrared and blue-green LEDs and corresponding PTs not shown)

2.1.3.2 Air-Blast Cleaning

Air passages were embedded in the sediment sensors for lens cleaning. The stretch-out views of the sensor tube with air outlets are shown in Figure 5.

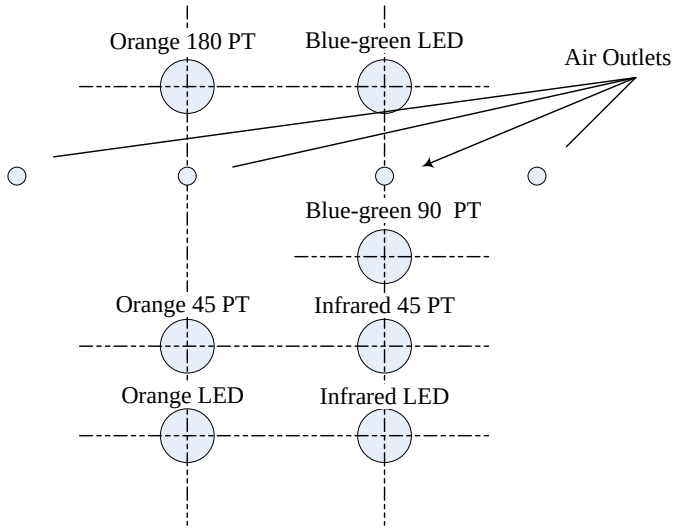

Figure 5. The stretch-out view of air outlets in the sensor tube with an acetal case.

A 12 volt (V) air compressor equipped with a 3.5 liter air tank was used to generate pressurized air. A solenoid valve was controlled by the PCB to blast air into the sensor at programmable intervals to clean the sensor lenses (Zhang, 2009).

2.1.3.3 Control

The control of the sensor included a PCB, voltage regulators, motes, data acquisition board, relays, temperature measurement, and interfaces.

2.1.3.4 Three-Tier Wireless Sensor Network

The three-tier WSN included three levels of networking: the LWSN, the mid-range sensor network (MRSN), and the LRCN.

The LWSN was in charge of transmitting data from sensors to a gateway station. On this tier, the area that the wireless transmission had to cover was usually near a stream or under a bridge, surrounded by trees and other vegetation. Commercial cellular coverage in these areas was generally poor or nonexistent, and required short range wireless devices (up to 100 meters [m]) to relay sensor signals to a gateway station, where signals could be further relayed.

The MRSN relayed the data, through a moderately long distance (up to 16 kilometers [km]), from the signal-unfriendly sensor sites to a location with a satisfactory commercial cellular coverage. Because of the longer transmission range, the MRSN allowed multiple LWSNs within a larger area to send data to the same central station, where they shared a single cellular service

to transmit the data to the Internet. A repeater station could also be added to the MRSN to further enlarge its coverage area.

The last tier in the three-tier WSN was the LRCN. It used a commercial mobile wireless data service to further transmit data to the database server through the Internet. A "Web-GIS" system developed in this project gave access to the database via the Internet. A block diagram for the three-tier WSN system is shown in Figure 6.

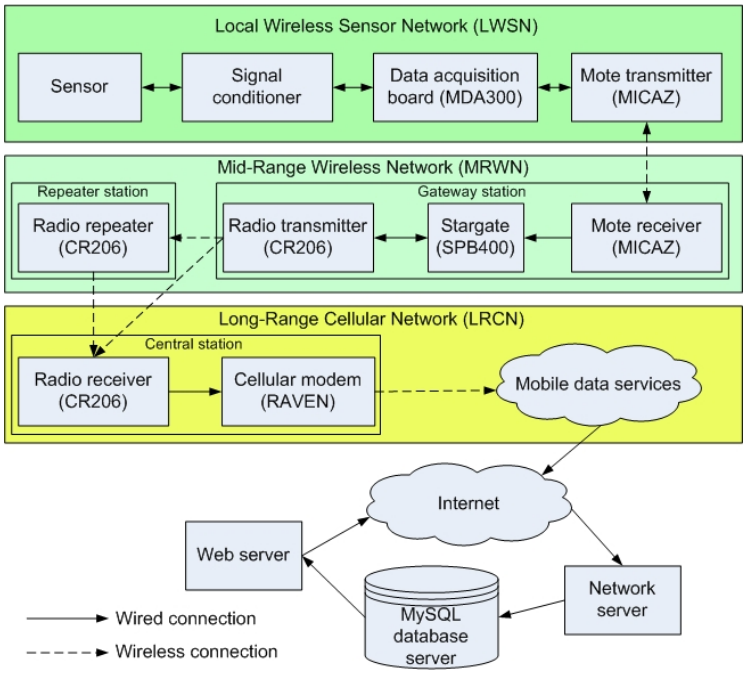

Figure 6. Block diagram for the three-tier WSN.

2.1.3.5 <u>WebGIS</u>

A WebGIS software package was developed to manage the data received from the sensors through the three-tier WSN. The software package was built upon two databases – a cache database and an archive database, which were synchronized through a database synchronizer. The WebGIS was developed to meet the following requirements:

1. Facilitate representation of data in different forms (e.g., tabular and graphical);
2. Allow users to generate customized queries;
3. Provide functionality to export data to different formats; and
4. View the location of sensors on maps for better understanding of the data.

The system also provided the following functions:

1. Daily summary report;
2. General-purpose report; and
3. Alerts for low battery levels.

2.1.4 Expected Applications of the Technology

The technology may be applied to remote monitoring of sediment transport and sediment load to assist studies of water erosion and wind erosion problems that are related to agricultural, construction, and military activities. The combined SSC and velocity sensor may be used to estimate discharge and sediment load at the watershed scale. It may also be used to estimate the life of reservoirs. For municipal water treatment plants, the sensor may be used to determine the optimal method for treatment, hence, reducing the treatment cost. The sensor may also be used in chemical plants to measure sediment in chemicals.

The WSN infrastructure may be used for large-scale, remote monitoring for other environmental and ecological studies, or studies related to climate changes.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Two methods that are typically used to estimate SSC are: 1) grab samples that are analyzed for turbidity or SSC; and 2) in-situ turbidity monitoring. Grab samples that are analyzed for turbidity provide an indirect measurement of SSC; the turbidity measurements must still be correlated to SSC using a correlation developed for the location where the sample was collected. Grab samples that are analyzed for SSC provide a direct measure of SSC. A disadvantage of this technique is that it is costly in terms of field work and lab processing, and it is time intensive. Grab samples do not have the temporal sampling resolution necessary to capture rapid intermittent flushes of suspended sediment during storms or other transient events, because the measurement is not continuous. They also lack the spatial resolution necessary to capture spatial variations in suspended sediment discharge across a channel (sediment samples collected at the same time across a channel can vary by a significant amount). Finally, the locations at which grab samples can be collected may be limited if sites are remote or otherwise inaccessible, or if sampling conditions are hazardous.

The optical sensors provide enhanced temporal and spatial resolution at a lower cost than grab samples. The optical sensors enable automated, continuous monitoring of SSC at reduced cost because they monitor SSC in situ, thereby reducing the number of water samples that need to be collected and analyzed at off-site laboratories. They also provide improved temporal sampling resolution and enable the capture of rapid intermittent flushes of suspended sediment during storms and other transient events. They can therefore better monitor rapidly changing SSC, such as tidally affected water bodies, when vehicles ford a creek or stream, or during storm events. They can better determine irregular re-suspension of sediment, as in the case of boat passage. Depending on the number of sensors installed at a single location, they can provide enhanced spatial resolution (both horizontal and vertical) at that location. For example, they can be installed at several depths to provide depth profiles of SSC. Another advantage of optical sensors when compared to the grab sample technique is that they can be installed at many locations for real time monitoring over a large area. They also can be installed at inaccessible locations, such as in marshes. They can perform real time monitoring under hazardous conditions, such as during storm events, when personnel cannot safely or easily go out to the sampling site to collect grab samples.

A limitation of the optical sensor is that it is susceptible to biofouling of the lenses. Biofouling is noticeable on the lenses after a very short time, and must be continually addressed. Another limitation is that the optical sensor is vulnerable to damage by high flow conditions, flotsam, vandalism, or other damage. Perhaps the most challenging limitation of the optical sensor is the need for grab samples that cover a sufficient range of sediment concentration for a good, location-specific calibration. Although the number of grab samples needed for calibration is small, the wide range of sediment concentration covered by these samples may be difficult to achieve within a short period of time.

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3.0 PERFORMANCE OBJECTIVES

The quantitative and qualitative performance criteria for the technology demonstration and actual performances measured during the demonstration are summarized in Table 1.

Table 1. Performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Accuracy in SSC measurement	SSC measurement error, as compared against laboratory analyses of grab samples, when water temperature is within 0-50°C.	SSC measured by sensor and laboratory analysis of grab samples	±10% or ±50 mg/L of actual SSC, whichever is greater.	For SSC>500 mg/L: Maximum error (95% confidence interval): -46.2% For SSC<500 mg/L: Maximum error (95% confidence interval): 291 mg/L
SSC measurement range	Range of SSC measurement, within which the accuracy in SSC measurement is achieved, when water temperature is within 0-50°C.	SSC measurement by sensor and laboratory analysis of grab samples	0-10,000 mg/L	0-5,000 mg/L
Repeatability of SSC measurement	SSC measurement error, as compared against laboratory analyses of grab samples under the following conditions: • When sensor repeatedly measures SSC within a small time span • When grab samples are taken at the same time, location, and under the same conditions • When water temperature is within 0-50°C.	Repeated SSC measurements by sensor and laboratory analysis of grab samples obtained at the same time and location, under the same conditions	±5% or ±25 mg/L of actual SSC, whichever is greater.	for SSC>500 mg/L: ±12.9% for SSC<500 mg/L: ±292 mg/L
Operability of anti-fouling mechanisms and correction algorithm to compensate data deterioration due to fouling	SSC measurement error, as compared against laboratory analyses of grab samples, for data taken within a two-month period without manual lens cleaning	SSC measured by sensor with anti-fouling mechanism and laboratory analysis of grab samples taken between manual lens cleanings	±10% or ±50 mg/L of actual SSC, whichever is greater	For SSC>500 mg/L 23.1% For SSC<500 mg/L 234.5 mg/L
Accuracy in flow velocity measurement	Flow velocity measurement error, as compared against velocity measured using an open-channel flow meter placed at the same location and same depth, when water temperature is within 0-50°C.	Flow velocity measured by sensor and flow meter	±10% or ±0.01 m/s of actual flow velocity, whichever is greater.	When using a commercial ultrasonic flow meter as reference: 27.75%

°C = degrees Celsius
mg/L = milligrams per liter

Table 1. Performance objectives (continued).

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives (continued)				
Flow velocity measurement range	Range of flow velocity measurement, within which the accuracy in flow velocity is achieved.	Flow velocity measurement by sensor and flow meter	0.01-5 m/s	0.125-4.5 m/s
Repeatability of flow velocity measurement	Flow velocity measurement error, as compared against an open-channel flow meter placed at the same location and same depth, when sensor repeatedly measures flow velocity within a small time span at the same time and location, under the same conditions.	Repeated flow velocity measurements by sensor and flow meter at the same time and location, under the same conditions	±5% or ±0.005 m/s of actual flow velocity, whichever is greater.	Repeatability limit: 0.37 m/s
Reliability of the SSC/flow velocity sensor	Percentage of total time when an SSC/flow velocity sensor normally measures SSC, and flow velocity within the demonstration period.	Record of times a SSC/flow velocity sensor unexpectedly stops to normally measure SSC and flow velocity (downtime) and resumes normal operation after repair (uptime)	Greater than 90% of the demonstration period, including high-flow season.	PNO: For SSC: 72.4% For velocity: 69.6%
Reliability of LWSN	Percentage of total time when an LWSN normally transmit data within the demonstration period.	Record downtimes and uptimes of each sensor	Greater than 90% of the demonstration period, including high-flow season.	PNO: 55.0%
Data loss rate of LWSN	Data loss rate (%) within the periods when an LWSN normally transmits data.	Recorded data losses for each LWSN	Less than 0.5%	0.45%
Reliability of MRWN	Percentage of total time when an MRWN normally transmits data within the demonstration period.	Record of downtimes and uptimes of each LWSN	Greater than 90% of the demonstration period, including high-flow season.	PNO: 64.7%
Data loss rate of MRWN	Data loss rate (%) within the periods when an MRWNs normally transmits data.	Recorded data losses for each MRWN	Less than 0.5%	(For both MRWN and LRCN) 8.83%

m/s = meters per second
PNO = percentage of normal operation

Table 1. Performance objectives (continued).

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives (continued)				
Reliability of LRCN	Percentage of the total time when an LRCN normally transmit data within the demonstration period.	Record of downtimes and uptimes of each LRCN	Greater than 90% of the demonstration period, including high-flow season.	70.5%
Data loss rate of LRCN	Data loss rate (%) within the periods when an LRCN normally transmits data.	Recorded data losses for each LRCN	Less than 0.5% s	(For both MRWN and LRCN) 8.83%
Reliability of Internet server	Percentage of total time when the Internet server normally operates within the demonstration period.	Record of downtimes and uptimes of the Internet server	Greater than 90%.	98.1%
Reliability of WebGIS	Percentage of total time when the WebGIS normally operates within the demonstration period.	Record of downtimes and uptimes of the WebGIS	Greater than 90%	98.8%
Reliability of solar panel and charging circuit	Percentage of total time when a solar panel and associated recharging circuit provides sufficient power within the demonstration period.	Record of downtimes and uptimes of each solar panel and associated changing circuit	Greater than 90% of the demonstration period, including high-flow season	74.1%
Reliability of alternative 1 for WSN - MBC system	Percentage of total time when the MBC normally transmits data within the demonstration period.	Record of downtimes and uptimes of the MBC system	Greater than 70% of the demonstration period, including high-flow season.	94%
Data loss rate of MBC	Data loss rate (%) within the periods when the MBC normally transmit data.	Record of data losses for the MBC	Less than 20%	1.1%
Reliability of alternative 2 for WSN - datalogger	Percentage of total time when the datalogger normally records data within the demonstration period.	Record of downtimes and uptimes of the datalogger	Greater than 90% of the demonstration period, including high-flow season.	100%
Data loss rate of datalogger	Data loss rate (%) within the periods when datalogger normally stores data.	Record of data losses for the datalogger	Less than 0.5%	0%
Qualitative Performance Objectives				
Degradation of sensor housing	Visual assessment of sensor housing; digital image features of fouling and corrosion.	Photograph, digital images	Minimal degradation or corrosion of sensor housing	Minimal degradation

MBC = meteor burst communication

In January, 2011, while requesting an extension for the demonstration, we added several qualitative and quantitative performance objectives. These new objectives are listed in Table 2 and 3.

Table 2. Quantitative performance objectives added in January 2011.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Reliability of WSN components that deliver data to memory cards at the gateways	(1) Number of events that cause complete loss of data, (2) Average and maximum durations of these events during a one-year period, and (3) Average and maximum durations of such events occurring during storm events and cold weather	Record of events and durations of the events that cause complete loss of data; weather condition when these events occur	The number of such events is less than 10; the average and maximum duration of these events are less than 30 days and less than 15 days, respectively.	Number of events for a sensor site: 15 Average duration: 59 days Maximum duration: 91 days
Reliability of WSN components that deliver data from the gateways to the database server	(1) Number of events that disable the remote, real-time monitoring but still preserve data in the memory cards, (2) Average and maximum durations of these events within a one-year period, and (3) Average and maximum durations of such events occurring during storm events and cold weather	Record of events and durations of the events during which the data is lost in the database server but is still stored in the memory cards at the gateways, weather condition when these events occur	Same as above	Number of events for a sensor site: 37 Average duration: 37 days Maximum duration: 186 days

Table 3. Qualitative performance objectives added in January 2011.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Ease of use of the technology	Skill level required to troubleshoot and maintain system components	Record of troubleshooting by non-electrical engineers in the team	Except the electronic circuits and mote/stargate programming, an engineering technician can troubleshoot and maintain the system and its components with an average time for fixing a component failure of one work day, and an average time between the same failures of one month.	Skill level required: engineering technician with training for some components
System maintenance requirements	Time required to troubleshoot and repair system	Time required to troubleshoot and repair system	Downtime during maintenance will not exceed an average of one work day to fix a component failure	6.5 hours (actual time spent after the technician arrived at the site)

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4.0 SITE DESCRIPTION

The experiment sites were selected from studies of digital maps and multiple field trips.

4.1 SITE LOCATION AND HISTORY

The following nine criteria/requirements are established for demonstration site evaluation and selection:

1. Candidate sites should be located on Department of Defense (DoD) facilities, or affiliated with (and near) a DoD facility.
2. Demonstration sites should be accessible so that test equipment can be installed and maintained easily.
3. Demonstration sites should have continuous flowing water; the water depth should be sufficient so that SSC sensors are submerged most of the time. One of the sites should be in an estuarine tidal environment.
4. Candidate sites must have facility acceptance of the demonstration technology.
5. The total suspended solids (TSS) should be sufficiently high in order for the sensor to be able to measure SSC concentration.
6. The various demonstration sites should be located in different geographical areas so that the sensors and WSN can be demonstrated under a variety of climactic conditions.
7. If possible, the demonstration sites should be close to existing water quality monitoring stations in order to leverage SSC, flow, and weather data being collected at those stations.
8. Demonstration sites should be selected in areas where measured SSC data is meaningful and helpful to the installations to perform ongoing or planned water quality monitoring programs.
9. At least one location within each experiment site should have cellular coverage to serve as the central station for long range data transmission. The sites of central stations selected at the three experimental sites should have different types of topography so that the three-tier WSN can be demonstrated under different types of terrain.

Three Army installations were selected for the demonstration: Fort Benning, Georgia; Fort Riley, Kansas; and Aberdeen Proving Ground (APG), Maryland. One or more “sensor clusters” were installed at each installation, with each sensor cluster consisting of one or more optical sensors. Sensor clusters at each installation were integrated into a three-tier WSN. The sensor clusters and the number of sensors comprising each cluster are shown in Table 4.

Table 4. Sensors deployed at the demonstration sites.

Installations	Sensor Sites	Number of Sensors Deployed
APG, Maryland	Edgewood Rod and Gun Club (Gunpowder River Pier)	2
	Otter Point Creek (Anita Leight Estuary Center)	2
Fort Benning, Georgia	Pine Knot Creek	2
	Upatoi Creek	2
Fort Riley, Kansas	Little Kitten Creek	1
	Wildcat Creek	2
	Silver Creek	1

4.2 SITE CHARACTERISTICS

Characteristics of the selected experimental sites at three military installations are described below.

4.2.1 Fort Riley, Kansas

Fort Riley was selected as a desirable location for this project because of its close proximity to KSU. This site can be classified under the Flint Hills Eco region, which is characterized by large rolling hills composed of shale and limestone. The average annual precipitation of the region is between 28-35 inches (Castle, 2007).The region is dominated by tallgrass prairie and remains mostly undeveloped in the study sites chosen. Three streams and four sensor sites where selected for this location. All of the streams used in this study are part of the Wildcat Creek basin. The four sensor sites selected at Fort Riley included the Little Kitten Creek (LK) site and the Wildcat Bridge (WB), Wildcat Creek (WC), and Silver Creek (SC) sites.

4.2.2 Fort Benning, Georgia

Fort Benning is dominated by evergreen and deciduous forest and has rolling hill topography (Bourne and Graves, 2001). The average annual rainfall for this area is approximately 49 inches (U.S. Climate Data, 2011). This site has a different climate, soil type, and ecological makeup from the Fort Riley site and provides the study with data to improve versatility. Two different streams – Pine Knot Creek and Upatoi Creek were chosen for this study site with two sensors installed in each stream. The streambed of these creeks is mostly sand that tends to settle very quickly to the bottom of the stream. This caused some difficulty in obtaining high SSC samples. Both sensors at this site were installed approximately 15 feet apart from each other with one sensor being slightly north and east of the other sensor.

4.2.3 Aberdeen Proving Grounds, Maryland

APG is located in Harford County, Maryland. The installation has about 72,000 acres, most of which are rangelands and water areas that are used for testing purposes. APG is actively involved in several environmental compliance, pollution prevention, conservation, and restoration programs. The ecological region of this area is defined as the outer coastal plain, mixed forest and is fairly developed (Doe III et al., 1999). The eco region is characterized by mostly flat topography with oak-hickory-pine forests being the natural vegetation (McNab and Peter, 1994).

The rivers in this area are mostly stagnant with their flow coming from tidal influence. Two sites were selected for this location with two sensors installed at each site. The distance between the two sites is 8.1 km.

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5.0 TEST DESIGN

The procedure designed for the experiment and demonstration is described in this section.

5.1 CONCEPTUAL TEST DESIGN

The experiment was designed to test: 1) performance of the SSC sensor in long-term, remote monitoring of sediment in streams at three military installations; 2) performance of the integrated SSC/flow velocity sensor in measuring flow velocity in open streams; and 3) performance of the three-tier WSN in transmitting and managing SSC and velocity data measured at multiple location within three military installations over a long period of time. The experiment was accomplished by deploying components of the system – sensor nodes, gateway stations, repeater stations, and central stations at the installations. The SSC measurement was calibrated against grab samples collected at the sensor locations. The velocity measurement was calibrated against a commercial ultrasonic flow velocity sensor, and the three-tier WSN was examined on failures and data loss.

Tasks of the experiment included: 1) lab testing of the flow velocity measurement capability and anti-fouling mechanism components added to the optical sensor, followed by field testing of the entire optical sensor node; and 2) lab and field tests of each tier of the three-tier WSN.

5.2 BASELINE CHARACTERIZATION AND PREPARATION

Characterization and site preparation activities that were performed prior to beginning demonstration testing included: 1) perform pre-calibration of the optical sensors; 2) determine the final locations of the individual gateway stations and central stations; and 3) installation of the optical sensor and ancillary components at the various demonstration sites.

5.2.1 Calibration of Optical Sensors for SSC Measurement

It was anticipated that the optical sensor signals would vary with the optical properties of the suspended sediment and the opto-electric components. For the best results, a calibration model needed to be developed for each sensor and for each location where the sensor was installed.

Pre-calibration of the sensor was performed using formazin stock suspensions, following the EPA standard 2130B (EPA, 1999). The gains of the sensor's signal conditioning circuits were adjusted so that the maximum sensor signals were achieved at a certain level of SSC Figure 7.

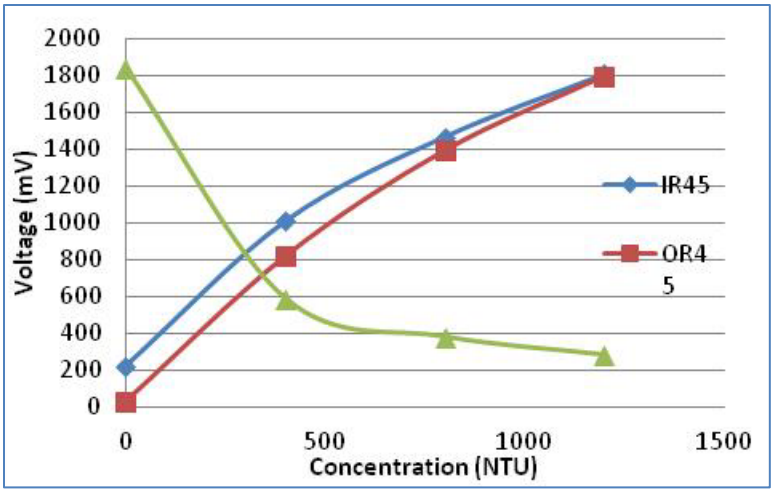

Figure 7. Pre-calibration curves of the sensors for Little Kitten Creek.

The second step was to establish the calibration model for predicting sediment concentration from the sensor signals for each sensor at its location of deployment. To develop this model, a large number of grab samples within a wide range of sediment concentration were needed. Actual sediment concentrations of these samples were measured using the filtering and weighing method in laboratory. A regression analysis of the actual concentration against sensor signals was then conducted to produce the calibration model.

5.2.2 Flow Velocity Measurements

Combined SSC/flow velocity measurement was demonstrated at two sensor site – the Little Kitten Creek site at Fort Riley and the Pine Knot Creek site, where the sensor was installed in the same cross section as the United States Geological Survey (USGS) stream gage #02341725.

5.2.3 Field Test of the Velocity Sensor

The field tests compared the measurements of the sensor to those from a commercial Flowtracker ultrasonic velocity sensor in an actual field installation. The goal was to determine if the sensor could properly detect the water velocity in real-world conditions where turbulent flow was present. Twenty-six separate tests were conducted in Little Kitten Creek comparing these sensors. In each test, multiple measurements were taken with both sensors.

5.2.4 Using USGS Stage Data and Point Velocity Measurement to Estimate Discharge

The stage data recorded at the USGS #02341725 gaging station at Pine Knot Creek at Fort Benning was compared with the velocity data measured by the SSC/velocity sensor deployed at the same location.

The air-blast cleaning mechanism installed on the sensor body was evaluated through a series of indoor tests.

5.2.5 Data Post-Processing to Remove Fouling Effect

The sediment was corrected for fouling through post-processing. The correction was done by determining the fouling trend through a regression analysis on peak signal values taken during no-rain periods. The fouling trend was then removed to restore the sensor signals. A MATLAB program was developed to complete the signal correction (Zhang, 2009). The regression curve was automatically developed based on actual data. Thus, the same program can be used for different sites without modification.

5.2.6 Alternatives of Three-Tier WSN –MBC and Datalogger Only Options

The MBC system as an alternative of WSN was also installed at the central station of the Fort Riley site, sharing the lower two tiers of the WSN with the three-tier WSN. The MBC central station was installed close to the central station of Fort Riley site. The MBC antenna was mounted at the top of a 10 foot (ft) steel conduit and pointed to the MBC master station at Tipton, Missouri, which is locates over 200 miles from Manhattan, Kansas. The central station received the SSC data from the sensor node at the Wildcat Bridge site and transmitted the data to the master station.

A datalogger-only option was considered as another alternative of the three-tier WSN. For this option, no wireless technology should be used. The SSC and velocity data should be stored in a memory card at each sensor node, and be downloaded into a computer manually at a later time. Thus, the measurement cannot be done in real-time.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY AND METHODOLOGY COMPONENTS

After the final locations of the optical sensors were identified, the locations of the gateway stations needed to be determined at all sites. The gateway stations should be located within 100 meters of the sensor nodes for acceptable signal reception. The locations were determined by field inspections at the sensor sites for ease of access and minimum impacts on other ongoing activities at the sites. The selection was also coordinated with, and approved by installation personnel. The final locations of the gateway stations were field validated before the wireless network components were installed at the site. Validation was performed by measuring received signal strength indicator (RSSI) at the locations of the gateway stations to ensure that signals can be transmitted from each of the sensor sites to the gateway station. The locations of the gateway stations were determined using a global positioning system (GPS) and marked on an appropriately scaled map.

Based on the locations of the gateway stations, a final location for the central station was determined at each installation. Several possible locations for the central station were first identified using installation maps. These locations were then assessed during field inspections, and the best location determined. The candidate sites for the central station were evaluated on: 1) strengths of signals received from the gateways at the central station as measured using a spectrum analyzer; 2) ability to transmit signals from the central station through the cellular network (i.e., cellular coverage at the central station); 3) ease of access; and 4) impacts to other ongoing activities. The final locations of the central stations were validated before the network

components were installed through a survey. The survey validated the signal strengths as indicated by RSSI at each selected gateway stations and the central station and the strength of cellular signals at the central station. The field survey also determined if any additional repeater stations were required to transmit signals from the gateways to the central station. GPS locations of the repeater and central stations were determined and marked on an appropriately scaled map. Also, the final location of the central and repeater stations at each installation were approved by installation personnel.

5.4 FIELD TESTING

5.4.1 Phase I - Further Development of Sensor and Three-Tier WSN

Phase 1 was conducted at KSU. During this phase, the sensor was further improved by adding a stream flow velocity measurement and a self-cleaning mechanism through simple structural expansions. The velocity measurement function was tested in an enclosed circulation system and in a flume. A commercial ultrasonic, open-channel flow meter was used to calibrate the sensor.

Two options for sensor lens cleaning were designed and tested: an air-blast cleaning system and an ultrasonic cleaning system. The ultrasonic system was found to consume too much of the battery power, which made it not practical for field use. The air-blast cleaning system was tested in both laboratory and field. Sensors with acetal and aluminum cases were tested at 2-minute and 12-hour cleaning intervals to observe the performance of the cleaning system. Signal recovery due to sensor cleaning was studied and the cleanness of the optical lenses was visually observed to qualitatively evaluate the effectiveness of the cleaning system.

5.4.2 Phase 2 - Sensor and WSN Test at the Pilot Experimental Site

During the second stage, multiple sensors were deployed to the Little Kitten Creek pilot experiment site in Manhattan, Kansas. An LWSN was established between the sensors and a gateway station located on the bank of Little Kitten Creek. Radio transceivers with Yagi and Omni antennas were installed at the gateway station, a repeater station, and a central station; all of which were located in Manhattan, Kansas. RSSI was measured using a spectrum analyzer to help determine the locations of the gateway station, repeater, and central station.

5.4.3 Phase 3 - Sensor and WSN Installation and Test at the Installations

During the third phase, multiple sensor nodes and WSNs were installed at Fort Benning, Fort Riley, and APG. Data packets consisting of SSC, flow velocity, water temperature, and precipitation were transmitted to the web servers at KSU and Oklahoma State University (OSU). A WebGIS was developed to allow access and utilization of the monitoring data. A daily report that contained statistics of data collected during the previous day and alerts about low battery voltages was sent to the project personnel each morning at 6 a.m. (central time) by the WebGIS system.

During the third phase, the MBC alternative was demonstrated at the Fort Riley site. The MBC system was used to replace the LRCS in the three-tier WSN.

During this stage, project personnel took several site visits to install the sensors and WSN, to debug and repair system problems, and to collect grab samples.

5.5 SAMPLING PROTOCOL

Calibration of the SSC sensors was composed of two stages – a pre-calibration conducted in the laboratory using formazin stock suspensions, and a field calibration conducted in stream using grab water samples. Water sampling provided the base for the second stage of sensor calibration – the field calibration. Water sampling was also the core action for sensor validation. At all sensor sites, water sampling has been conducted throughout the experiment to provide sufficient numbers of grab samples for SSC sensor calibration and validation. The SSC of the water samples were measured following the standard weighing/filtering procedure.

The data was then matched up with the sensor signals in the online database recorded at the same time in order to find a correlation between sensor signal and SSC. Sensor signals were then plotted against measured concentrations to determine the relationship between the signals and SSC (Bigham, 2012).

5.6 SAMPLING RESULTS

After the sensors were deployed to the three installations, it was found that the SSCs of the water samples taken from the sensor sites were generally low. With the exception of one grab sample taken during a rain event at the Silver Creek site, the maximum sediment concentration obtained from these samples was 232 mg/L, which was only about 1/20 of the expected range. If calibration was limited to these grab samples, the effective measurement range would be very narrow. As a result, the measurement accuracy within a wider range of SSC would suffer greatly.

Due to this situation, the Project Team requested a one-year extension for field demonstration (from July 1, 2011 to June 30, 2012) in March 2011. In order to derive better prediction models, the Project Team decided to make the following changes:

1. Knowing that the actual sediment concentration range at the sensor locations was generally much lower than the range assumed in pre-calibration, the gains of the sensors were adjusted so that the measurement ranges were reduced. This adjustment was accomplished in laboratory by replacing several resistors on the signal conditioning board. This gain adjustment will become a part of sensor calibration before a sensor is deployed to a specific site. It is performed only once for each sensor, and it is always done in the laboratory.
2. Increasing the number of grab samples taken from all sensor sites.

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6.0 PERFORMANCE ASSESSMENT

Performance of the system is assessed against each performance objective listed in Table 1.

6.1 ACCURACY IN SSC MEASUREMENT

Accuracy of the SSC sensor was assessed using grab samples collected at each sensor site. For each sensor, one half of the grab samples along with sensor signals received at sample collection times were used to establish "calibration models" to predict SSC from the sensor signals. The remaining half of the grab samples were then used for validation.

6.1.1 Calibration Models

Calibration models were established through statistical analyses of measured SSCs, and grab samples taken at the sensor sites on a site-by-site basis. Table 5 displays the sites and time periods in which the water samples were taken along with the SSC ranges observed.

Table 5. Water sample data displaying number of grab samples taken at each site, period samples taken, and range of concentration of water samples.

Sensor Location		Number of Grab Samples Taken	Time Period the Grab Samples Were Taken	Range of Sediment Concentration (mg/L)	Daily Precipitation (inch)		
					Min.	Max.	Avg.
Fort Riley	Little Kitten	24	5/17/2011 – 11/08/2011	7.3 – 815.6	0.00	2.11	0.11
	Wildcat Bridge	17	5/20/2011 – 12/3/2011	8.0 – 4685.1	0.00	2.11	0.11
	Wildcat Creek	2	5/25/2011	106.7 – 116.3	1.07	1.07	1.07
	Silver Creek	2	5/25/2011	105.1– 190.3	1.07	1.07	1.07
	Total	45	5/17/2011 – 12/3/2011	7.3 – 4685.1			
Fort Benning	Pine Knot North	14	4/1/2011 – 4/13/2012	2.9 – 27.9	0.00	3.28	0.10
	Pine Knot South	11	4/1/2011 – 4/13/2012	0.7 – 90.2	0.00	3.28	0.10
	Upatoi North	14	4/1/2011 – 4/13/2012	7.2 – 34.8	0.00	3.28	0.10
	Upatoi South	22	7/5/2011 – 4/13/2012	4.0 – 31.4	0.00	3.28	0.12
Total		61	4/1/2011 – 12/21/2011	0.7 – 90.2			
APG	Anita Near	25	4/28/2011 – 12/20/2011	2.43 – 461.4	0.00	1.02	0.08
	Anita Far	23	4/28/2011 – 12/21/2011	11.2 – 729.1	0.00	1.02	0.08
	Total	48	4/28/2011 – 12/21/2011	2.43 – 729.1			
	Grand Total	154					

Water samples taken at each site were divided into two sets – a calibration set and a validation set. Figure 8 shows the regression model to predict SSC using the ORA180 data recorded for the Little Kitten sensor site.

The best second order polynomial model found for Little Kitten was:

$$\text{Concentration (mg/L)} = 0.006*[\text{IR45 (mV)}]^2 - 2.43*\text{IR45 (mV)} - 0.255*\text{OR180(mV)} + 740$$

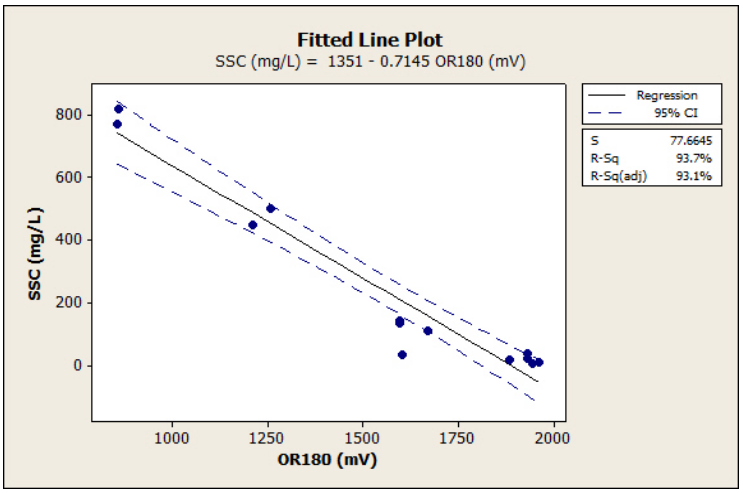


Figure 8. Regression model to predict the suspended sediment concentration using OR180 signal for Little Kitten Creek, Manhattan, Kansas.

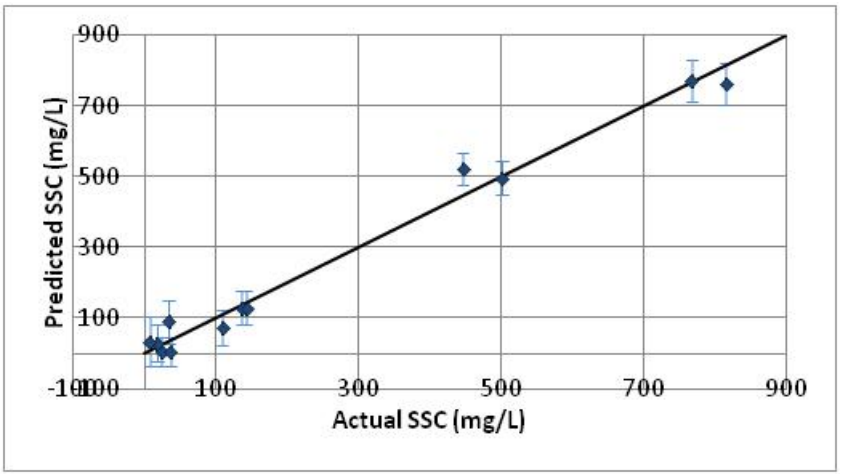


Figure 9. Predicted SSC versus actual SSC for the Little Kitten sensor using a second-order polynomial calibration model.

6.1.2 Model Validation

Half of the water samples taken at a site were used in validation. The calibration data set was entered into Minitab to establish a calibration model through regression. The validation data set was then entered into the calibration model to see how it fits in the calibration model. Root-mean-square error (RMSE) values were calculated for both calibration and validation data sets.

Figure 10 shows the predicted SSCs for both the calibration and validation data sets against the actual SSCs for the Little Kitten site. Also shown in the plots are the 95% confidence intervals for the validation data.

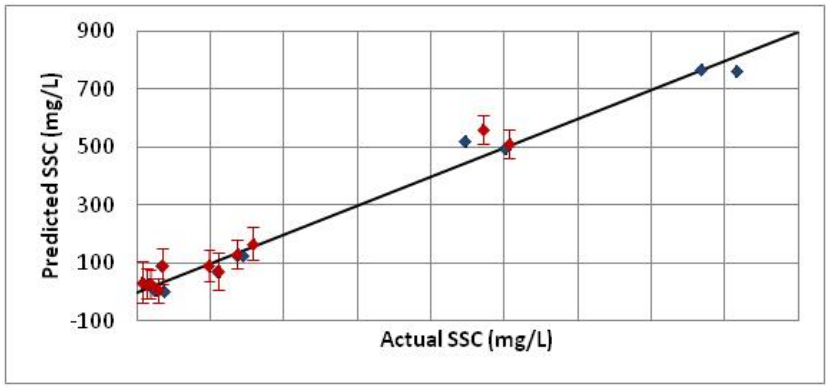


Figure 10. Predicted SSC versus actual SSC of the calibration and validation data sets for the Little Kitten sensor site using second-order calibration model.

Table 6 summarizes the accuracy of SSC measurements for all sensor sites. Results reported in this table were only for the validation data sets. In Table 6 and Table 7, red-colored items indicate failures to pass the success criteria. It is safe to say that for the Upatoi North, Pine Knot North, Pine Knot South and Anita Near sites, the sensors passed the success criteria for SSC below 500 mg/L. However, because of the low range of SSC, the measurement accuracy was not satisfactory.

Table 6. Summary of SSC measurement range and accuracy.
(For validation data sets only)

Site (Range)	Model Type		Maximum Error (Measure 1)		Maximum Error (95% confidence interval) (Measure 2)	
	Order	Signal(s) used	# 500mg/L (mg/L)	>500mg/L (%)	# 500mg/L (mg/L)	>500mg/L (%)
Little Kitten (0 – 500 mg/L)	2	IR45, OR180	91.6	1.2	142.0	10.8
Wildcat Bridge (0 – 4000 mg/L)	1	OR180	117.8	5.6	173.2	9.1
Upatoi North (0 – 35 mg/L)	1	OR180	6.6		13.8	
PineKnot North (0 – 30 mg/L)	1	IR45	-10.6		-15.2	
PineKnot South (0 – 90 mg/L)	1	OR180	8.5		29.5	
Anita Near (0 – 120 mg/L)	1	OR45	42.2		55.3	
Anita Far (0 – 700 mg/L)	1	IR45	201.0	-21.2	290.9	-46.2

For sites like Little Kitten, Wildcat Bridge, Anita Near, and Anita Far where the success criteria were not met, lack of evenly distributed samples within the SSC range affected the prediction models. For instance, the Wildcat Bridge site had clustered samples below 100 mg/L, but was lacking samples within the mid-range of SSC.

Overall, the best models in each site used either IR45 or OR180 signals, or combination of these two. Linear model was also found to be generally more accurate in predicting SSC.

6.2 SSC MEASUREMENT RANGE

As demonstrated at the Wildcat Bridge sensor, SSCs of higher than 4000 mg/L were successfully measured using the sensor. The range of SSC measurement was mainly determined by the gain of the current-to-voltage converter in the signal-conditioning circuit of the sensor, which was adjustable and was selected during the sensor pre-calibration based on expected SSC range. A previous study has shown that 5000 mg/L was not difficult to achieve (Figure 11).

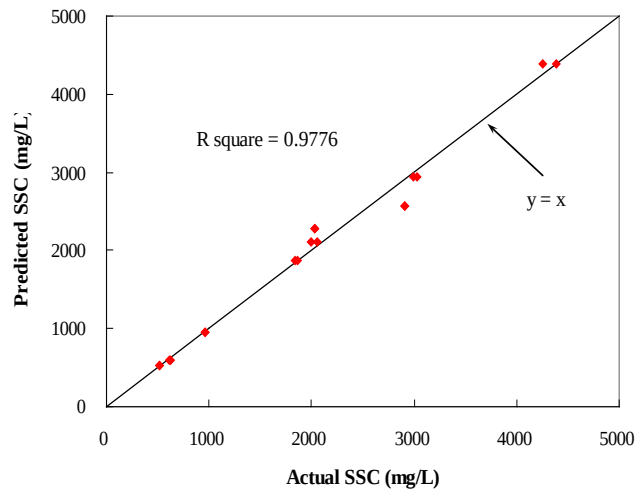


Figure 11. SSC measurement range.
(Zhang, 2009)

6.3 REPEATABILITY OF SSC MEASUREMENT

Table 7 shows the standard deviation, coefficient of variation, and repeatability limit (at 95% confidence level) of each measurement considered. The success criteria for repeatability limit were +5% or +25 mg/L, whichever is larger. The repeatability limits that did not pass the success criteria are colored red. From the table, it can be observed that larger repeatability limits were found at higher SSC readings.

Table 7. Repeatability limits for the SSC prediction models.

Site	Model	Sample	Measured SSC (mg/L)	Sd (mg/L)	CV	Repeatability Limit (mg/L)	Repeatability Limit (%)
Little Kitten	OR180 model	1	183.6	14.6	0.08	43	
		2	94.5	6.5	0.07	19	
	IR45-OR180	1	184.6	14.4	0.08	42	
	2nd order	2	75.5	7.8	0.10	23	
WC	OR180 model	1	141.3	99	0.7	292	
		2	1835	80.4	0.04		12.9%
Upatoi North	OR180 model	1	35	8.1	0.23	24	
		2	27.8	8.2	0.29	24	
	OR45-OR180	1	34.7	11.6	0.33	34	
	model	2	25.9	13.1	0.5	39	

CV = coefficient of variation
Sd = standard deviation

Table 7. Repeatability limits for the SSC prediction models (continued).

Site	Model	Sample	Measured SSC (mg/L)	Sd (mg/L)	CV	Repeatability Limit (mg/L)	Repeatability Limit (%)
Pine Knot North	IR45 model	1	8.8	4.0	0.46	12	
		2	25.3	4.4	0.17	13	
	IR45-OR45model	1	8	5.1	0.63	15	
		2	25.1	6.3	0.25	19	
Pine Knot South	OR180 model	1	29.6	6.5	0.22	19	
		2	30.2	6.8	0.23	20	
	IR45-OR180model	1	35.6	11	0.31	32	
		2	37.5	12.1	0.32	36	
Anita Leight Near	All signals	1	55.4	14.6	0.26	43	
		2	37.4	11.9	0.32	35	

6.4 OPERABILITY OF ANTI-FOULING MECHANISMS AND CORRECTION ALGORITHM TO COMPENSATE DATA DETERIORATION DUE TO FOULING

Figure 12 shows the results of laboratory test of the air-blast system. The signals shown in this figure were measured during a 40-day period. Figure 13 gives a close-up view of the first four days of data. The effect of the air-blast system can be clearly observed from the sharp spikes on the IR45 and ORA180 signals. It can also be seen from Figure 12 that signal deterioration accelerated about 28 days after the experiment started, indicating that, the cleaning mechanism could only maintain the lenses clean for a limited period of time, beyond which the mechanism had only a limited effect on reducing lens fouling.

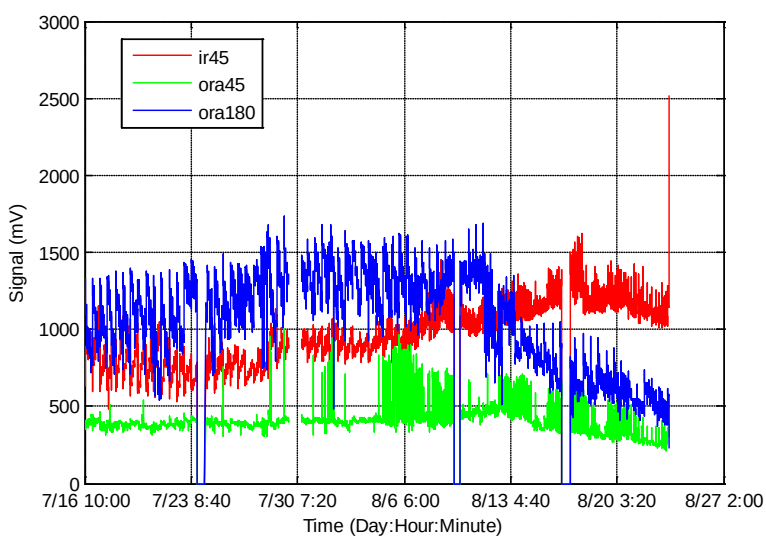


Figure 12. A 40-day laboratory test on air-blast cleaning.

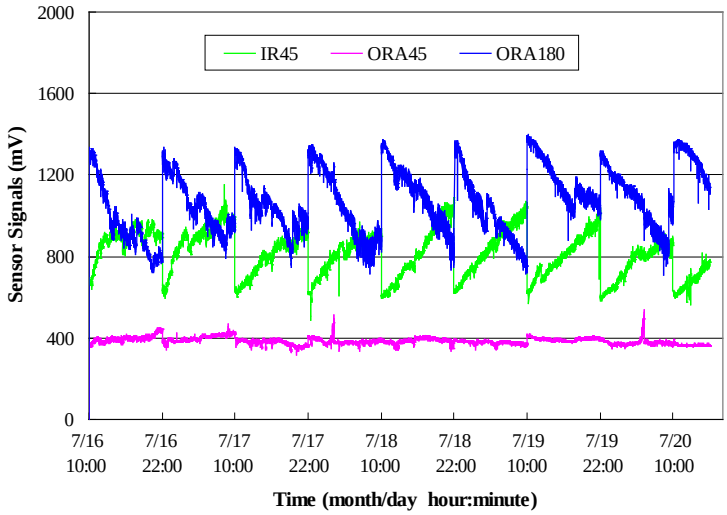


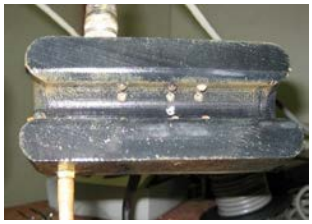
Figure 13. A close-up view of the first four days of data.

Figure 14 compares two sensors, one with air-blast cleaning and one without. Both sensors were left in stream water for 16 days. The effectiveness of the air-blast cleaning system can be easily observed.

Sensor with air-blast cleaning

Sensor without air-blast cleaning

Sensor with air-blast cleaning



Sensor without air-blast cleaning

Figure 14. Photographs comparing sensors with and without air-blast cleaning after a 16-day cleaning experiment.
(November 26 – December 12, 2008)

Maintenance of the air blast system has been a challenge. The life span of the air compressor seemed to last only a few months. The large electric power required to run the air compressor often caused the system to power down. After the air compressor was installed, the air hose would often detached from the compressor, especially during strong storms.

With the ability to keep the sensor lenses clean for a certain period of time, the air-blast system allowed longer intervals between manual cleanings. To further reduce the effect of fouling on long-term SSC monitoring, the post-processing data correction algorithm was used to further

remove the fouling effect. Figure 15 shows data collected during a six-month period (May 1 – October 31, 2011) from the Little Kitten sensor site. Figure 16 shows the SSC calculated after the data was corrected for fouling/clogging.

In Table 8, the SSCs measured from the fouling/corrected ORA 180 signals are compared against the actual SSCs of the grab samples taken during this period of time. Also shown in the table are measurement errors calculated in mg/L for SSCs below 500 mg/L, or in percentage for SSCs higher than 500 mg/L.

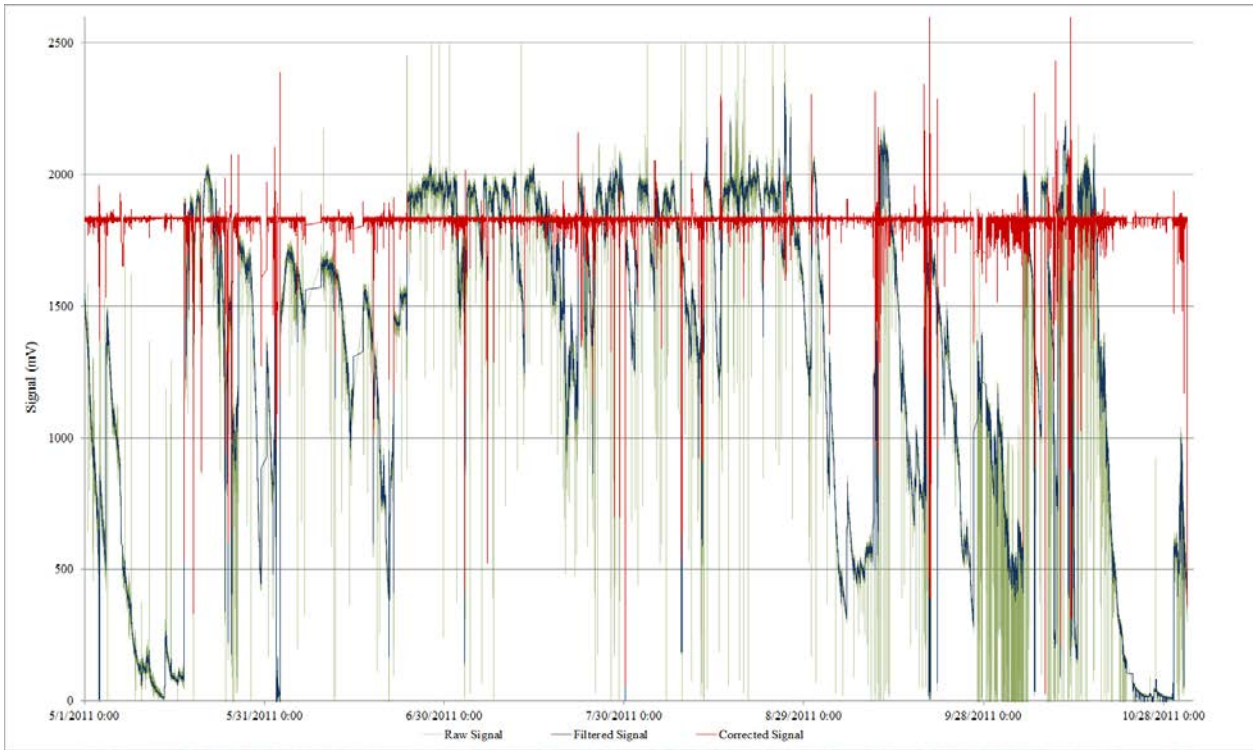


Figure 15. The ORA 180 signal collected for the sensor at the Little Kitten site during a six-month period – from May 1 – October 31, 2011.
The signal was first filtered and then corrected for fouling and clogging.

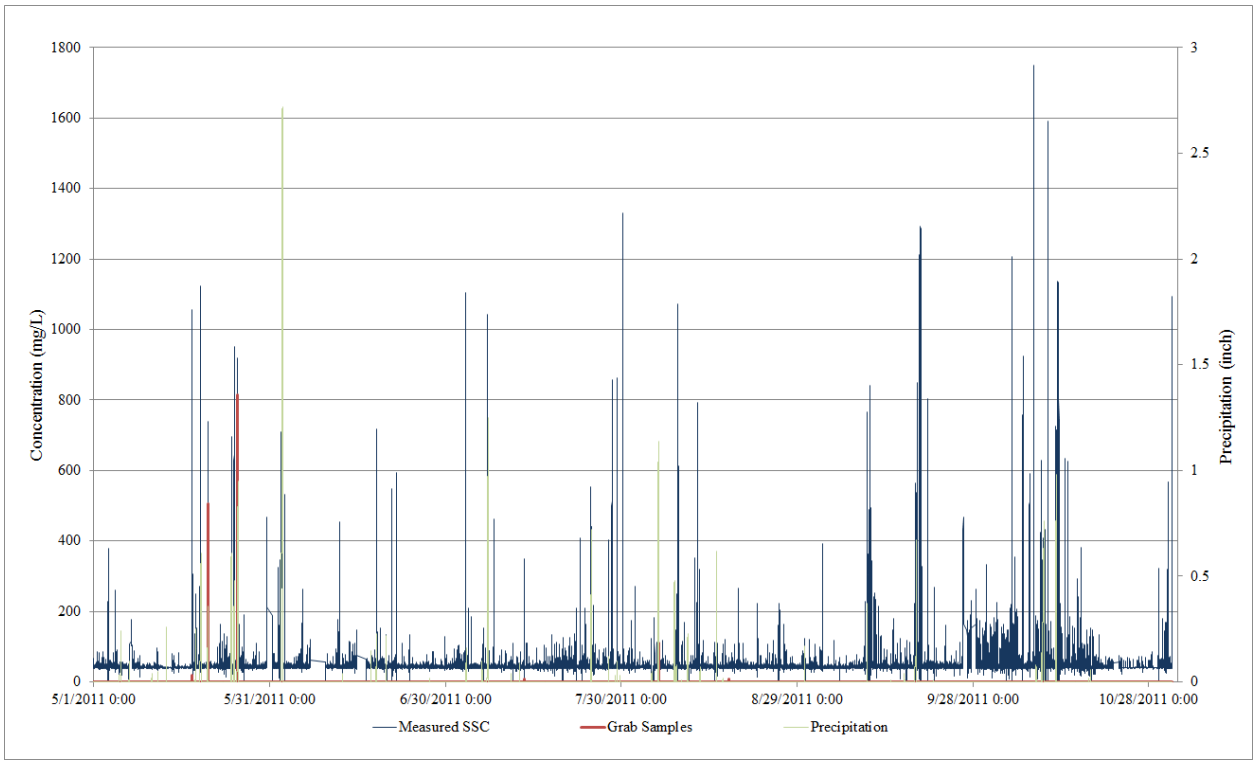


Figure 16. SSC measured using the clogging/fouling corrected ORA 180 signals during the May-October period at the Little Kitten site.

Table 8. Comparison of SSC measured from the fouling/clogging corrected signals against the actual SSC for the grab samples collected in May 2011, at the Little Kitten sensor site.

Actual SSC (mg/L) (grab samples)	Measured SSC (mg/L) (from corrected ORA 180 signal)	Error (mg/L)	Error (%)
13.54	42.51	29.0	
17.32	41.82	24.5	
18.73	64.71	46.0	
23.59	14.01	-9.6	
28.80	22.18	-6.6	
33.85	0	-33.8	
34.75	0	-34.7	
36.75	17.98	-18.8	
136.24	219.82	83.6	
136.48	217.32	80.8	
143.07	215.51	72.4	
446.77	676.86	230.1	
471.08	705.58	234.5	
500.89	616.68		23.1
506.32	639.01		26.2
767.66	811.13		5.7
815.63	811.3		-0.5
Mean		53.6	13.6

6.5 ACCURACY IN FLOW VELOCITY MEASUREMENT

Accuracy of the sensor in velocity measurement was examined mainly through field tests.

6.5.1 Field Test of Velocity Sensor

Velocities measured using the Flowtracker ultrasonic sensor and the SSC/velocity sensor at the Little Kitten sensor site are plotted against each other in Figure 17. A linear relationship between the measurements across the entire velocity range tested, from about 0.25 m s^{-1} to about 1.66 m s^{-1}, is apparent.

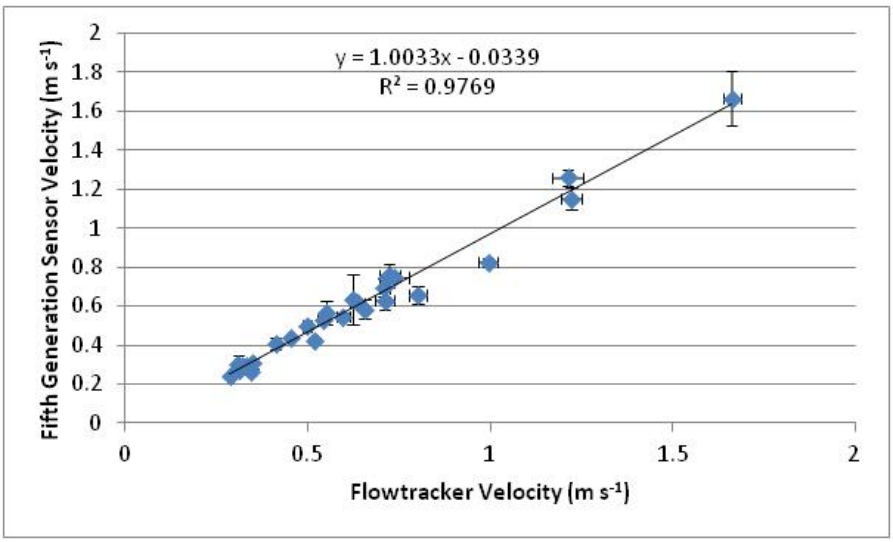


Figure 17. Comparison of velocities measured by the 5th Generation Sensor and the Flowtracker with 95% confidence intervals.

6.5.2 Predicting Discharge Using Point Velocity Measurement

During this study, a SSC/flow velocity sensor was placed at a Pine Knot sensor site where the "USGS 02341725 Pine Knot Creek Near EelBeeck, GA" stage monitoring station was located. The purpose of this arrangement was to compare the velocity data with USGS stage and discharge data and to study the possibility of using the point velocity measurement provided by our sensor to either help simplify the discharge estimation procedure or to provide better discharge estimates.

For many years the USGS has estimated stream discharge in rivers and streams across the United States mainly using two methods – the stage-discharge method and index velocity method (Olson and Norris, 2007).

The index-velocity method utilizes continuous records of both stage and an index velocity to estimate discharge. This method requires that two rating curves be developed. The first relates stage to area and the second relates the index velocity to the mean velocity of the water in the channel profile. The results of these ratings are mean velocity and cross sectional area, which can be multiplied together to produce the discharge of the stream (Levesque and Oberg, 2012).

In this study, the stage-area rating curve required for this method was developed using the USGS AreaComp program based on cross-section survey provided by USGS. The index rating, which relates the index velocity to the mean velocity, was normally done by manually taking many separate discharge measurements using an acoustic Doppler current profiler (ADCP) or the mid-section method and comparing them to the index velocity. These discharge measurements need to cover the entire range and types of flows for the site. Unfortunately, at Pine Knot only three separate discharge measurements were made with the mid-section method while the index velocity sensor was operating. These did not cover the full range of flows and were insufficient to generate an index rating curve.

However, the USGS had previously measured discharges within a wide range of flows and created a stage-discharge curve for the station at the site. From this, they have been providing discharge estimates at the cross section every 15 minutes. In a departure from the standard index velocity application, one half randomly selected USGS discharge estimates for the gage station were converted to mean velocities using corresponding stage measurements and the stage-area rating.

The velocity sensor installed in Pine Knot Creek took four velocity measurements each hour with each measurement separated by 30 seconds. All good measurements from a single hour were averaged together to produce the velocity estimate from the sensor for that hour. The hourly velocity measurements were further smoothed using a 24-hour moving average to produce the index velocity. A regression analysis provided a linear equation between the mean velocities and index velocities measured at the same time and, thus, the index rating curve (Figure 18).

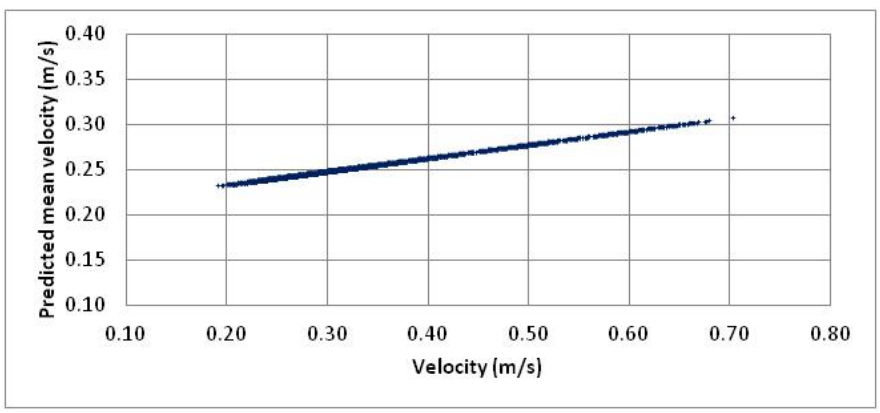


Figure 18. The index-rating curve that relates point velocity measurement to mean velocity for Pine Knot Creek.

After both the stage-area and the index rating curves were created, the second half of the velocity and stage measurement data, which were not selected when creating the curves, were used to produce discharge estimates. First, the stages measured by the gage station were used with the stage-area rating to estimate areas. Next, the mean velocities were determined by the index velocities measured by the sensor and the index rating curve. Multiplying the mean velocities and the areas resulted in the discharge estimates, which were used to compare with the USGS discharge estimates for validation. Figure 19 compares the estimated discharges against discharges reported by USGS.

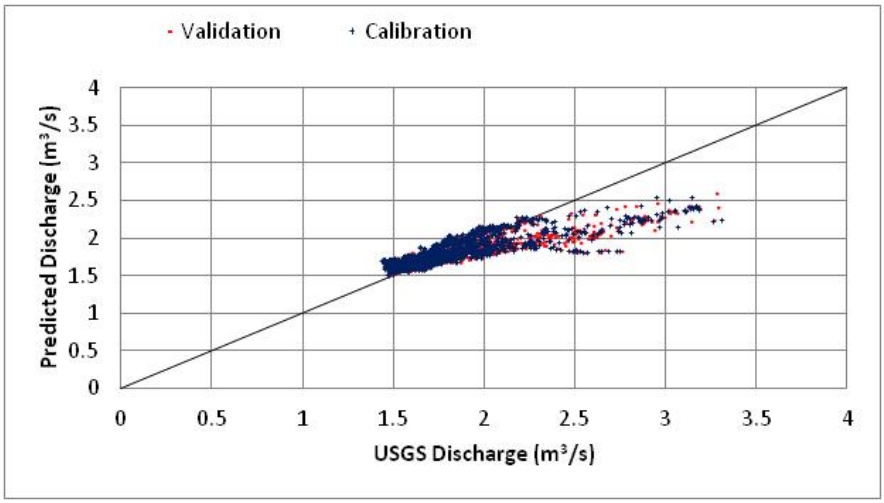


Figure 19. Estimating discharge from point velocity and stage measurement for Pine Knot Creek.

A statistical analysis showed that, for the validation data set, the 95% confidence interval for the discharge estimate using the velocity sensor was ±1.03 m^3/s. It is clear that, for both the calibration and validation data sets, higher discharges (above $2m^3/s$) were slightly underestimated.

This experiment demonstrated the possibility of using both stage and point velocity measurements to estimate discharge. Further experiments may help validate and further refine the method proposed in this report.

6.6 FLOW VELOCITY MEASUREMENT RANGE

The velocity sensor was tested in a closed circulation system in laboratory within the range of 0.125-4.5 m s^{-1}. Figure 20 compares the measured velocities against true velocities. The mean percent error obtained on the validation data set was below 10%.

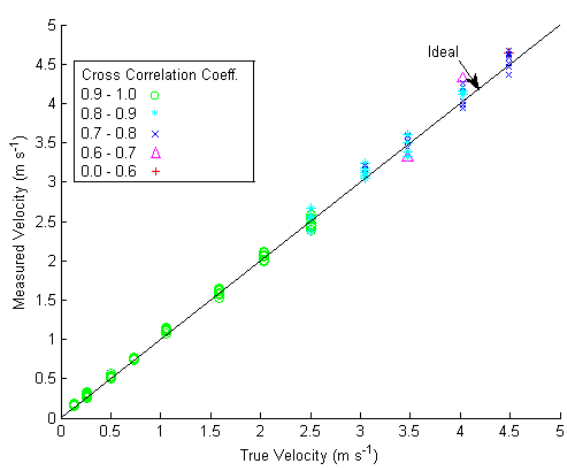


Figure 20. Measured against true velocities for the validation data set.

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7.0 COST ASSESSMENT

Cost of the three-tier WSN system was compared with other options of system configuration.

7.1 COST MODEL

Costs related to the SSC sensor/WSN technology demonstration were fully tracked. The types of costs that were tracked included procurement (capital) costs, labor costs, cost of installation, training, start-up costs, operational costs, maintenance costs, and costs for documentation and laboratory analytical service. The actual cost for the WSN that covered 12 SSC sensors at three installations was $26,950.

7.2 COST DRIVERS

For the sensor, installation and maintenance are the major cost drivers. The installation cost is dependent on the site characteristics. Installing the sensor and associated gateway station/solar power system in narrow streams with dense vegetative covers usually requires much greater cost on labor and materials. Usually, more frequent maintenance trips to these sensor sites would also add significant cost.

For the WSN, the need for repeater stations is often a major cost driver. This is especially true for rural sensor sites where no cellular coverage is available. Directly providing cellular devices to each LWSN would eliminate the need for MRWN, hence reducing the cost for hardware and initial installation. However, recursive charges for continuous data services by the cellular companies may eventually even out this saving.

7.3 COST ANALYSIS AND COMPARISON

The most popular technologies for measuring SSC are grab sampling followed by laboratory analysis.

In order to collect the grab samples, a technician must travel to the field and manually collect water samples at the site(s) of interest. Depending on the number of sites and the distance that needs to be travelled, this can take hours or even days. Samples are typically sent to an off-site laboratory for gravimetric analysis.

Table 9 compares costs related to five options for SSC monitoring. The first option is the SSC sensor and the three-tier WSN that has been demonstrated through this project. Option 2 replaces the top tier of the three-tier WSN with the MBC technology. An obvious drawback of Option 2 is that only 1/10 of the SSC data can be transmitted and stored. Option 3 avoids all wireless technologies and places a datalogger with sufficient memory space at each sensor. Obviously, this option cannot provide “real-time” data.

Table 9. Cost comparison between different technologies.

Option	1	2	3	4	5
Technology	Three-tier WSN	MBC for top tier	Dataloggers only	Manual sampling	Pump sampler
Quantity of measurements	2880/day	288/day	2880/day	24/day	24/rain + 24 for baseflow
Total cost	$115,423	$119,578	$98,576	$701,670	$65,408

Option 4 is the traditional grab sampling and consequent laboratory analysis without using any of the sensing and WSN technologies. The cost for this option is based on an assumption that at least one grab sample is taken every hour, which would total 8760 samples for a year, and it would require 8760 trips to the site to take the samples and transport them to the laboratory. Thus, while proving very few samples, this option would involve a very high labor cost. Of course, if this is done consistently throughout the year, it still can be considered "long-term" monitoring.

The last option uses an automatic pump sampler, such as the popular in situ chemical oxidation (ISCO) sampler. The sampler can be programmed to take samples either by preset times or upon rain event triggering. Because the sampler contains multiple sample containers (24 for a typical ISCO sampler), and it can be triggered by water level, which is in turn triggered by rain events, fewer samples would be needed. Assuming 30 rain-triggered events with an average duration of one day each within a year, if 24 samples are taken for each event, the total number of water samples taken by the sampler within a year would be 720. If, in addition, two base flow samples are taken each month, the total number of samples would add up to 744. On the other hand, because the sampler can hold multiple samples (24 in the case of the ISCO sampler), the number of trips required for sampling would be reduced to 54 (30 to take samples and reset the sampler after each rain event and 24 to take base-flow samples). Savings from the reduced requirement for travel would be great. Although this option cannot provide "real-time" and "continuous" data, the data it provides may be meaningful and sufficient for many applications.

8.0 IMPLEMENTATION ISSUES

Several issues encountered during the demonstration were deemed important to the practical application of the technologies.

8.1 SSC SENSOR CALIBRATION ISSUE

The biggest concern with the SSC sensor was the difficulty in collecting water samples that cover a sufficiently wide range of sediment concentration for calibration. If the two-stage calibration procedure requires a long-term, field collection of water samples, especially during the raining season, this sensor may not find wide acceptance among the potential users.

In order to alleviate this concern, we started to think about an alternative approach for the second stage of sensor calibration since late 2011. The approach was to develop a continuously operated field sampler that continuously takes water samples at various sediment concentrations and completes the sampling process within one to two hours. From late 2011 to early 2012, several brainstorming meetings were held, and, in February 2012 a sampler was designed and fabricated. This sampler was used at six sensor sites, two at Fort Riley and four at Fort Benning.

The Project Team recommends using the sampler for stage 2 of sensor calibration because the sampler allows the sensor to be calibrated in the same stream where it is deployed and this ensures similar water and soil conditions between calibration and actual measurement; and use of this sampler would greatly reduce the time and effort needed to take grab samples and avoid the long wait for significant precipitation events to cover the desirable SSC measurement range.

When using the sampler for calibration, 10-12 SSC levels need to be created by adding local soil into the circulation system, and three to four replicated measurements are recommended for each SSC level. A regression analysis will then be conducted to allow prediction of SSC from single or multiple sensor signals.

8.2 SSC/VELOCITY SENSOR DEPLOYMENT ISSUES

For practical uses, the SSC/velocity sensor is always deployed in natural waters, including stream, lakes, rivers, and reservoirs. Securing the sensor in the water is always a challenge, especially during the high-flow season. The Project Team had several experiences when the sensor was partially or completely damaged by water flow. Adding mechanical reinforcement usually alleviates the problem. However, for streams with sand/stone bottoms this may become extremely difficult.

While being deployed in stream, the SSC/velocity sensor has the following connections to the PCB control board, which is located on the bank near the sensor: 1) signal wires to transmit the analog signals from the sensor to the PCB and control wires to transmit digital signals from the PCB to the sensor for LED illumination control; 2) air hose to lead pressurized air to the sensor for cleaning; 3) thermocouple wires to measure water temperature; and 4) (if velocity is measured) dye hose to lead color dye to the sensor. These connectors/hoses should be placed in a single conduit for protection.

The size of the stream needs to be considered when deploying the sensor. The general recommendation is that the sensor be deployed near a bank, perhaps within a distance of 20 ft. This recommendation is mainly based on concerns of the conduit length and the depth of the water. The velocity sensor has a maximum measurable velocity of 5 m/s. If the water velocity is expected to exceed this limit, the sensor should not be deployed. The maximum measurable SSC is 5000 mg/L. Therefore, the sensor should not be deployed in stream with expected SSC higher than 5000 mg/L.

During demonstration, the Project Team had several experiences where the sensor was buried by sands in locations where the water depth was sufficiently large when the sensor was first deployed. These experiences showed that, when selecting sensor locations, history of topography changes of the locations should be considered.

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APPENDIX A

POINTS OF CONTACT

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