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CENS
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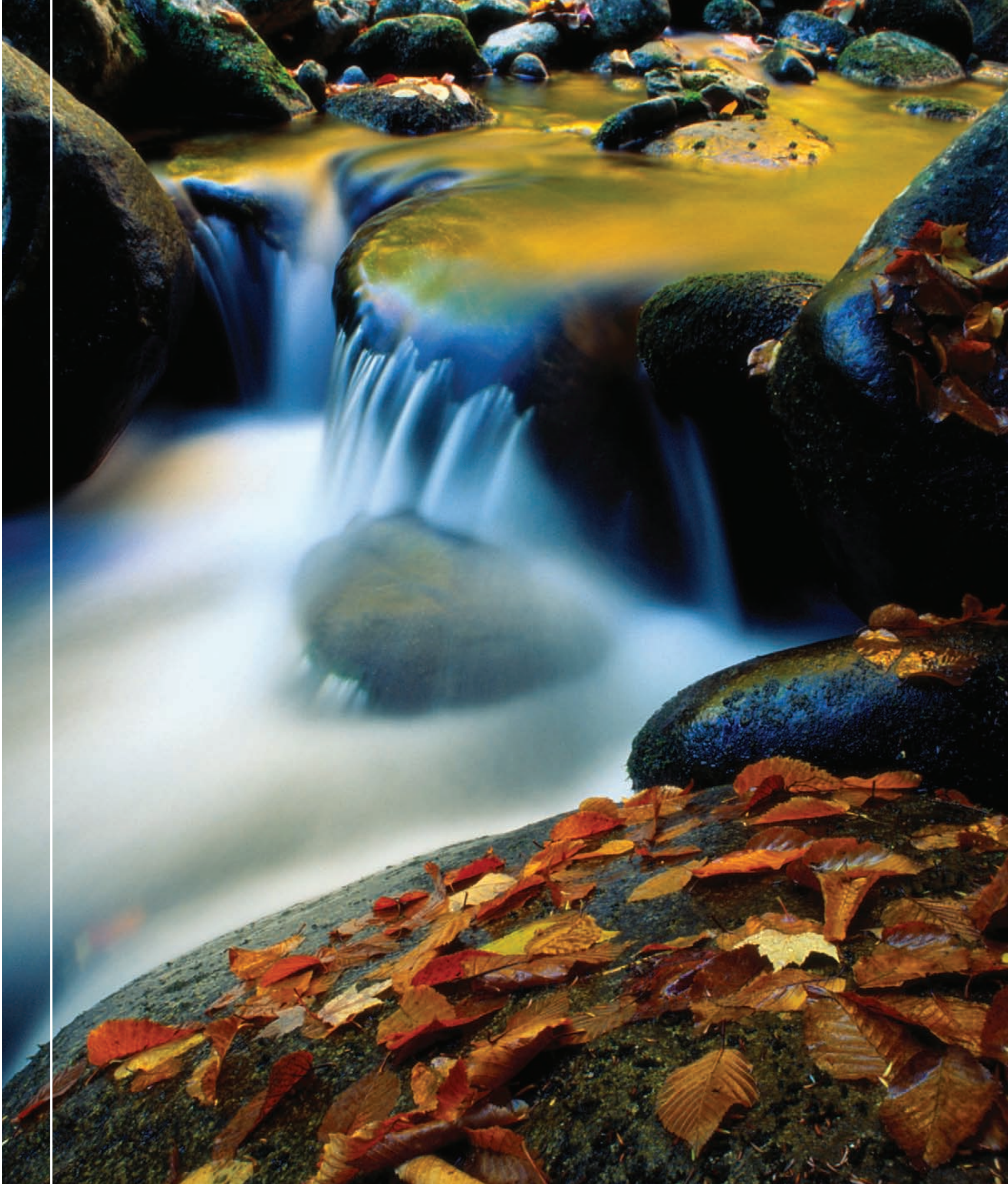

WHITE PAPER

Distributed Sensing Systems for Water Quality Assessment and Management

FEBRUARY 2007

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PREFACE

Environmental managers are hungry for data. In order to make decisions that assure the health and safety of human health and our environment, they must seek out and gather extensive information on environmental phenomena. Water quality managers ask: What are the heavy metal and chemical levels in a community's drinking water? Is the level of beach contamination too high for kids to swim? When does a septic system require service? Has a sewer reached capacity during a rainstorm? What is the quantity of agricultural and urban runoff? Getting answers to these questions requires constant monitoring and assessment by many parties every day. Yet, new tools are becoming available that *sense* these and many other environmental attributes, report that information, and can trigger a human or automatic response to an environmental threat.

Sensor network systems distributed in the environment present enormous opportunities for streamlining data collection efforts, getting real-time information, and achieving environmental management objectives at lower costs. Importantly, many applications can be built on top of distributed systems that already exist, or will be commercialized, thereby drastically reducing development and deployment times. Finally, these systems can be designed to match data collection and analysis to problems of varying geographic and temporal scale.

This white paper, written and illustrated by an interdisciplinary team of staff, students, and faculty at the Center for Embedded Networked Sensing (CENS) at UCLA, provides an overview of the state of the technologies, possible applications, and areas where critical research is needed. This paper highlights a wide-array of opportunities that these systems present for environmental management efforts at the Environmental Protection Agency (EPA), with a special focus on water-related issues. It also lays out a clear set of research objectives for those interested in accelerating the development and use of these systems by EPA or others.

—David Rejeski
Director, Foresight and Governance Project
Washington, DC
February 2007

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EXECUTIVE SUMMARY

The exponential progress of technology development, driven in many cases by Moore's Law, has enabled the combination of sensing, computation and wireless communication in small, low-power devices that can be embedded directly in the physical environment. Recent research has resulted in several new classes of embedded networked sensing systems that can be rapidly distributed in the environment to study phenomena with unprecedented detail. Embedded networked sensing systems are transforming the way in which physical, biological and chemical changes are detected and quantified. These results are leading to new mechanistic understanding of the environment and, consequently, to new models and predictions for better assessment and management of environmental challenges.

This white paper describes the emerging technologies used in distributed sensing systems and the opportunities these systems present for environmental management, and in particular, water quality protection. A team of faculty, students, and staff at the Center for Embedded Networked Sensing (CENS) wrote the report. CENS is a National Science Foundation sponsored Science and Technology Center, headquartered at the University of California, Los Angeles (UCLA). In addition to UCLA, the California Institute of Technology, the Riverside and Merced campuses of the University of California, and the University of Southern California are partners in the center. CENS is developing embedded networked sensing systems and applying this technology to critical scientific and social applications. The Foresight and Governance Project at the Woodrow Wilson International Center for Scholars edited and finalized this document for the U.S. Environmental Protection Agency's Office of Water.

This paper first briefly describes the potential applications of sensing systems to four common water quality management problems. This potential includes: (1) providing early warning for septic systems, (2) allowing for the trading of credits for non-point source runoff, (3) monitoring beach water quality, and (4) management of combined sewer overflows. Section 4 describes these scenarios in further detail.

Section 1 provides an overview of sensors (i.e., the devices that convert environmental phenomena into an electronic response) and actuators (i.e., the devices that convert electrical signals into mechanical responses). Sensors have the potential to detect physical, chemical, biological, and radiation properties in the environment. A variety of sensors is currently available for networked environmental sensing, while others are still in early research and development phases. Physical sensors for water quality monitoring are generally the most field-ready and scalable to distributed applications, followed by chemical and then biological sensors. The costs for these sensors depend on the physical, chemical, or biological parameter of interest. Indicator sensors and event-triggering sampling can be used when direct detection sensors are not ready for field deployment. To more extensively detect environmental properties, even more sophisticated sensors and sensing strategies are needed, including: (1) hardening novel sensors types (such as lab-on-a-chip technology) to withstand harsh conditions for extended periods, and (2) devising integrated sensing systems for higher order observations, such as quantifying materials fluxes in the environment.

Section 2 on Deployment Platforms discusses three new sensing system classes: static, mobile robotic, and mobile handheld. These sensing systems differ from traditional measurement systems in that sensors are attached to wireless radios that enable real-time communication of the data collected. For any particular situation, the best system class to use depends on the environment's spatial and temporal variation. Among the three classes of sensing systems, mobile handheld systems are best used when the environmental phenomena of interest cover a broad area and do not require great spatial resolution. Static sensing systems are best used over smaller areas when high spatial resolution is not required, and mobile robotic systems are appropriate for intensive measurement of very small areas. To improve overall sensing efficiency (e.g., time or cost), adaptive sampling allows the system to dynamically adjust its measurement location or frequency to meet spatial or temporal variation in the environment. Sensing platforms can also be combined such that different platforms can provide information at different scales. This type of multi-scale system can also often help improve the efficiency of a monitoring effort. Despite the opportunities these sensing systems present, the ability to deploy them in the field can be limited by power availability and faults that interfere with communication or sensing hardware.

To help address some of the challenges facing the effective implementation of sensing systems and the interpretation of the acquired data, section 3 discusses the usefulness of considering the entire "life cycle" of data in a sensing system. This life cycle consists of three distinct phases: design and deployment of the observing system; operation and monitoring; and analysis, modeling and data sharing.

The final section of the report offers recommendations for future research. In spite of the substantial success in research and development activities that has given rise to existing sensing systems, relatively few have been deployed in real-world applications. The time is ripe to expand the range of applications where embedded sensing systems are used. Some of the key recommendations outlined in section 5 for novel uses of embedded sensing systems include:

Sensors and Actuators

- *(1) Long-term research and development for sensors where new or improved detection methods are needed and (2) short-term market incentives targeted at moving already well-developed sensing technology from research prototypes (e.g., biological and chemical sensors) to commercially available products.*
- *Long-term research to develop detection methods for carbonaceous compounds, heavy metals, large molecular mass molecules such as dissolved organic compounds and dissolved organic nitrogen compounds, pathogenic organisms, biologically-active compounds, biomarkers, and lab-on-a-chip sensors.*
- *Research on methods to minimize sensor maintenance in the field.*
- *Investments to bring prototype technologies, such as small robust nitrate sensors that can be deployed for long periods, to market in forms suitable for environmental sensing.*

Deployment Platforms

- *Investments in a range of pilot studies to determine specific deployment and analysis methodologies for target systems (e.g., septic system or sewage discharge monitoring).*
- *Definition of requirements of large scale uses of the technology to encourage the production of user-friendly systems.*

The Data Life Cycle

- *The encouragement of pilot deployments to test and refine data management tasks for specific applications.*
- *Continued research and testing of tools to improve system robustness and ensure high-quality data.*
- *Additional focus on the integration of sensing systems with external data sources and third-party applications, especially map-based visualization with tools for both rigorous GIS techniques and more public friendly web applications.*

Training

- *Training at multiple levels (school systems and professional development) to ensure that a ready workforce exists that is prepared to use these new sensing technologies.*

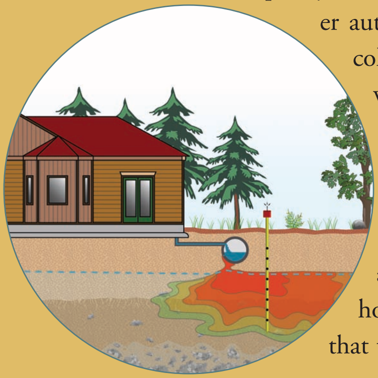
Embedded networked sensing systems will form a critical infrastructure resource for society—they will monitor and collect information on such diverse subjects as plankton colonies, endangered species, soil and air contaminants, medical patients, and buildings, bridges and other manmade structures. Investments in further research to help bring the sensing technologies discussed in this report into practice will transform the way we monitor and manage the health of our natural resources and predict and respond to crises.

Four Scenarios Describing the Potential Application of Sensing Systems to Water Quality Management

This section highlights four potential applications of distributed sensing systems that could help address and manage water quality problems. See section 4 for further detail on these scenarios.

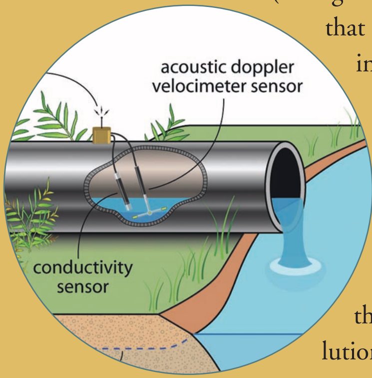
EARLY WARNING FOR SEPTIC SYSTEMS

After taking a routine reading of a water meter, a technician with the municipal water provider uses a handheld computer to locate the wireless signal from a battery-powered water quality sensor. The technician's computer automatically receives the data collected during the preceding weeks, analyzes it and determines that the septic system may be leaking. The homeowner's record is updated in the municipal database and a notice is sent to the house alerting the homeowner that the system requires service.



TRADING CREDITS FOR NON-POINT SOURCE RUNOFF

A county invests in a program to help farmers reduce polluted runoff. Data from a county-wide system of sensors placed in groundwater wells and surface collecting drains (see figure on left) is fed into a model that calculates a subsequent drop in the flux of total dissolved solids entering and leaving the county. Having quantified this drop in pollution, the county earns pollution reduction credits and trades them with other counties that experience increased pollution loads.



MONITORING BEACH WATER QUALITY

Sensors placed in the waters along the coast of a popular summer tourist destination regularly monitor the properties of the water that are predictors of unhealthy conditions. Computational analysis of the data is performed by the sensing system, which sends alerts to officials when water quality conditions are dangerous. Officials immediately issue warnings to beachgoers to avoid the unhealthy waters.

MANAGEMENT OF COMBINED SEWER OVERFLOWS

As a result of heavy rain, a city's combined sewer system sometimes overflows, discharging untreated sewage into the local river. After investing in a sensing system that recognizes when flows exceed the sewer's capacity and triggers valves to shunt excess water into holding tanks (rather than discharging it into the river), the city realizes substantial improvements in the river's water quality.

1. SENSORS AND ACTUATORS

Sensors and actuators connect *in situ* (or embedded) sensing systems to the environment. Sensors are devices that convert phenomena such as fluid motion, chemical potential, or the presence of a pathogenic microorganism into an electronic response. Actuators are devices that convert electrical signals into mechanical responses, often to initiate or execute an automatic process, such as the collection and preparation of an environmental sample. A diverse set of sensors is currently available for networked environmental sensing and new sensors will become available in the future. However, new sensor types and sensing approaches are still needed to monitor a continuously changing spectrum of critical environmental properties. In many cases, actuators can bridge the gap between sensors that exist now and those slated for development by efficiently collecting environmental samples for conventional analysis in a laboratory. Coupling *in situ* sensing with traditional laboratory analysis enabled by actuation is a powerful mechanism for protecting human health and the environment. Thus, both sensors and actuators are important parts of the discussion of environmental sensing systems.

1.1 SENSING MODES, FIELD-READINESS, AND SCALABILITY

Environmental sensors are usually categorized in terms of the physical, chemical, and biological properties they sense. In the context of environmental monitoring with embedded sensing systems, it is also important to assess (1) a sensor's *readiness* for field deployments and (2) a sensor's *scalability* to distributed environmental monitoring tasks (i.e., small and inexpensive enough to scale up to many distributed systems). Physical sensors relevant to water quality monitoring are generally more field-ready and scalable than chemical sensors, which are, in turn, substantially more field-ready and scalable than biological sensors (see figure 1.1). The sections below discuss the availability of sensors in these categories and the associated research and development needs.

Physical Sensors

Availability: Key physical parameters such as volumetric flow rate, flow velocity, pressure (or hydraulic head), depth, temperature, evapo-transpiration rate, light transmission (or turbidity), light quality, soil matric potential, and soil moisture content are all readily observable using sensors in robust, field-ready forms (figure 1.2) for observations in natural and engineered water systems. Many physical sensors are relatively inexpensive, ranging from \$10–\$100 (e.g., temperature sensors) to \$100–\$1,000 (e.g., moisture content sensors), making them scalable to large deployments. More costly exceptions exist, such as sophisticated light sensors (\$1000s) and acoustic Doppler velocimeters (\$10,000s), which are capable of producing distributed velocity fields over a wide

Figure 1.1

Sensor Category	Parameter	Field-Readiness	Scalability	Cost (USD)
Physical	Temperature	High	High	50–100
	Moisture Content	High	High	100–500
	Flow rate, Flow velocity	High	Medium–High	1,000–10,000
	Pressure	High	High	500–1,000
	Light Transmission (Turbidity)	High	High	800–2,000
Chemical	Dissolved Oxygen	High	High	800–2,000
	Electrical Conductivity	High	High	800–2,000
	pH	High	High	300–500
	Oxidation Reduction Potential	Medium	High	300–500
	Major Ionic Species (Cl^-, Na^+)	Low–Medium	High	500–800
	Nutrients[a] (Nitrate, Ammonium)	Low–Medium	Low–High	500–35000
	Heavy metals	Low	Low	NA
	Small Organic Compounds	Low	Low	NA
	Large Organic Compounds	Low	Low	NA
Biological	Microorganisms	Low	Low	NA
	Biologically active contaminants	Low	Low	NA

Figure 1.1 Examples of environmental sensors and their field-readiness, scalability to distributed sensing application, and cost.
[a] Data for nutrient sensors are based on nitrate; the large range includes ion selective electrodes (medium field-readiness, high scalability) on the low end and flow-through type instruments on the high end (medium field-readiness, low scalability). NA=Not available.

range of spatial scales. Given the importance of light in detecting microorganisms and velocity distributions in surface water systems, this price is often justifiable.

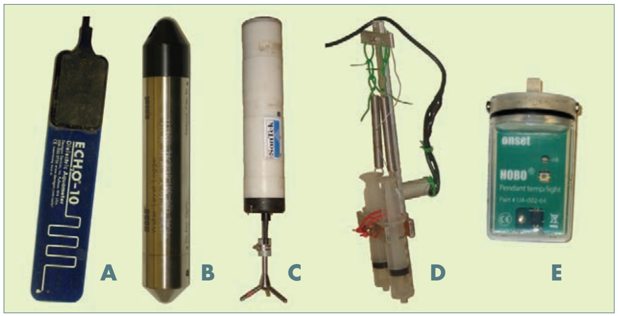


Figure 1.2 Examples of physical sensors and actuators. (A) Decagon Echo moisture sensor. Probe works well in medium-textured soil types with low EC conditions. In these soils without calibration, it is accurate to ±4%; with soil-specific calibration, it can achieve accuracy of ±1%. (B) HOBO water level data logger. Used to record water levels and temperatures in wells, streams, lakes, wetlands and tidal areas. The logger is completely self-contained. (C) Acoustic Doppler Velocimeter (ADV) from Sontek. Versatile, high-precision instrument used to measure 3D water velocity. (D) Physical sampling device with elastic actuator. Used to collect water samples remotely for detailed lab analysis. (E) HOBO Pendant temperature and light data logger. Device is waterproof and can record approximately 28,000 combined temperature and light readings.

Needs: Further miniaturization of many physical sensors and their electronics combined with rugged packaging will enhance their field-readiness, scalability and performance to distributed monitoring situations. A field-ready, miniaturized particle size-distribution and morphology sensor that can discriminate between biological and non-biological micro- and nanoparticles is one example of a physical sensor that is currently unavailable but needed for distributed water quality monitoring.

Chemical Sensors

Availability: Sensors for many basic water quality parameters are commercially available in multi-parameter packages, such as data sondes, that are suitable for harsh environmental conditions (figure 1.3). Available sensors include dissolved oxygen, electrical conductivity as an indicator of salinity and total dissolved solids (TDS), pH, oxidation-reduction potential, and fluorescence as an indicator of chlorophyll concentration and phytoplankton biomass (ACT 2005a). Some common ionic species, including chloride and sodium as well as nutrients, such as nitrate and ammonium, are readily available for laboratory analyses in the form of ion selective electrodes (ISE). The use of ISE technology in field deployments is limited by its relatively low sensitivity and reliability. In many cases it is important to detect trace concentrations on the order of parts per billion. However, for systems where such low detection limits are not necessary (e.g., agricultural runoff and septic fields) new materials are leading to more robust ISEs. Nitrate ISEs have been successfully piloted in several long-term field tests (Scholefield et al. 1999, 2005; Le Goff et al. 2003). Other work aimed at creating more suitable form factors (e.g., sizes and shapes) for nitrate and other ISEs is also ongoing (Bendikov et al. 2005; Bendikov and Harmon 2005).

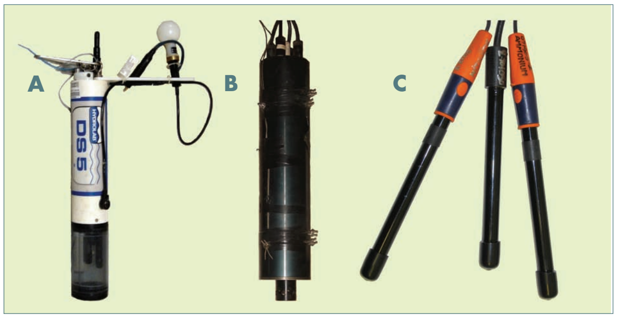


Figure 1.3 Examples of chemical sensors. (A) Hydrolab DataSonde 5 Multiprobe. Senses photosynthetically active radiation, depth, oxidation reduction potential, turbidity, temperature, pH, electrical conductivity, and luminescent dissolved oxygen. (B) In Situ Ultraviolet Spectrophotometer (ISUS). Measures concentration of dissolved ultraviolet absorption spectrum for nitrate. (C) Sentek ion-selective electrodes. Measures ammonium and nitrate concentration.

Needs: Chemical sensor needs abound across a broad spectrum of inorganic contaminants. Next-generation sensors in this domain should be long-lasting, calibration-free, scalable, and able to detect carbonaceous compounds, all common ions, nutrients (including all the major nitrogen and phosphorous species), trace metals, and biologically-pertinent compounds as noted below. While great strides have been made on the development of sensors to detect specific nutrients such as the *in situ* ultra-violet spectrometer or ISUS (Johnson and Coletti 2002), sensor packages for quantifying total nitrogen and total phosphorus are critical to expanding our understanding of nutrient cycling and loading (ACT 2003a). Sensors that can detect a variety of metals on the order of parts per trillion are of increasing concern because some heavy metals (e.g., Zn, Cu, Pb, and Cd) contribute to contamination of closed water bodies, such as lakes, and some metals (e.g., Fe, Mo, and Cu) are micronutrients that affect phytoplankton production in aquatic ecosystems (ACT 2005b).

In addition, there is a clear need for sensors that are capable of detecting organic compounds of both small (less than 300 Da[1]) and large (greater than 300 Da) molecular mass. Small molecules include xenobiotics such as halogenated

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[1] Da (Dalton) ≈ 1.66×10^{-27} kg.

hydrocarbons, other industrial toxins such as fuel components and their by-products (e.g., polycyclic aromatic hydrocarbons), and biologically produced substances such as methane, dimethyl sulfide, and bacteria- and phytoplankton-produced toxins (e.g., saxitoxin, brevetoxin, and dolomic acid) that threaten human health and ecosystem function. Compounds of large molecular mass, including dissolved organic compounds, have not received much attention. These compounds can play a large role in lowering dissolved oxygen concentration and in facilitating the transport and biological uptake of hydrophobic toxins.

Biological Sensors

Availability: Laboratory-based approaches to biological sensing are well established. For instance, detecting the presence and abundance of pathogenic bacteria, protozoa, and viruses; the abundances of harmful bloom-forming cyanobacteria and algae; and the concentrations of toxins produced by certain cyanobacteria and algae is fairly routine. Unfortunately, these techniques are generally time consuming—requiring several hours to several days for microscopy, culture, some form of chemical, genetic, or immunological analysis—and thus are not easily transferable to *in situ* sensors. Therefore, the development of sensors for routine, in-the-field identification and quantification of potentially harmful microorganisms, such as pathogenic bacteria and viruses, and naturally occurring or introduced biologically-active compounds, such as phytoplankton toxins and endocrine disruptors, is a high-priority for environmental science, in general, and environmental biology, in particular.

Currently, few field-ready sensors can detect important biological entities and their by-products. Although research into such sensors is taking place (MBARI 2006, USF 2005), the application of these sensors has been limited due to the sophisticated nature of the instruments and their high cost. Unlike other categories of sensors, the shortfall of small, robust biological sensors that can be deployed in the field constrains the use of distributed sensing systems in environmental biology.

Needs: In general, biological sensors must be sensitive enough to detect their target at low concentrations in the presence of a complex background matrix. For example, few microbiological sensor technologies can detect the presence of a target organism at concentrations below 103 cells/mL. Until more sensitive detection systems are developed, lower-concentration detection can be achieved by concentrating target molecules or cells from relatively large volumes of water.

One of the newest areas of sensor development involves detecting biomarkers. Biomarkers include molecules, chemicals, cells, and even large debris and are indicators of a change in biological system function (e.g., biological stress or metabolic shifts in biological communities). Linked with systems-level information, biomarker sensing offers the potential for direct ecosystem-level assessment. For instance, biomarkers can be used to indicate that a biological community or ecosystem is stressed due to changes in metabolic composition or the induction of key stress biomarkers. Currently, real-time sensing of the presence of biomarkers requires expensive instrumentation, however, the development of lower cost instruments continues through miniaturization offered by micro- and nanotechnology. The most typical and expensive methods used to detect biomarkers are techniques based on mass spectrometry, Fourier transform-infrared spectroscopy, and nuclear magnetic resonance spectroscopy. While these more sophisticated tools can detect overall fingerprints of several biomarkers at once, less expensive functional methods, such as immuno response-based microarrays and surface-enhanced Raman scattering (SERS), can also provide important information about the biological health of an environment. Both immunoassay and SERS offer superior levels of sensitivity and specificity relative to other methods, but they have not yet been developed in a way that enables reliable field deployment. Thus, they represent a critical investment need that stands to yield significant benefits.

Radiation Sensors

Availability: In addition to physical, chemical, and biological sensors, research and development surrounding distributed wireless sensing systems for radiation detection has shown great potential. Prototype systems that combine static and mobile detectors and on-board processing are progressing (Dreicer et al. 2002). This "distributed sensor network with collective computation" (DSN-CC) (Dreicer et al. 2002) or "sensor fusion" (Rennie 2004) allows for the combination of data from node to node within the network and between different sensing systems. Researchers at Los Alamos National Laboratory, in collaboration with the University of Mexico, are developing a flexible, discrete system of sensor arrays set up along a two-lane road that could detect a radiological dispersion device transported in a vehicle along that road (Brennan et al. 2004). This type of detection triggers a rapid response that could prevent the detonation of radioactive isotopes in a densely populated area.

Needs: To bring this technology into real-world applications, further research is needed to better understand "the technical decisions and trade off between cost, simplicity, detection efficiency, and network density," taking into account power use and system size (Dreicer et al. 2002). More refinement of the detector technologies is also needed (Brennan et al. 2004). Further research is underway. Students at the University of North Carolina at Pembroke participated in experimental research on chemical and radiation sensor development during the summer of 2006 (UNCP 2006). Brookhaven National Laboratory is developing a variety of sensors with the ability to "detect trace quantities of nuclear, chemical, and biological agents and explosives," (Brookhaven 2005). Future technologies may involve nano-sensors that could detect early radiological exposure inside the body (AVS 2002).

1.2 INDICATORS AND ACTUATED SAMPLING

When sensors for direct detection are not available for field deployment, indicator or event-triggering sensors can be used to great advantage. Indicator sensors measure parameters that correlate with the presence of targets and can be used as proxies or sentinels for imminent or emerging threats. As described above, chemical proxies and biomarkers for biological processes can be used in cases where direct sensors are not available.

Event-triggering sensors can be used to actuate the collection of physical samples for analysis in a laboratory. For example, in the wake of a discharge event, it is useful to know whether dangerous levels of pathogenic organisms are present in the receiving body. Since direct pathogen sensors are not yet available, a turbidity sensor could be used instead. Spikes in turbidity could trigger actuated sample collection for lab-based pathogenic analyses, thereby using a commercially available embeddable sensor to enable efficient, targeted water quality analysis despite the lack of available pathogen sensors. Physical sampling is also often required to ensure accurate calibration for chemical and biological sensors, which are known to drift and exhibit distortion due to saturation and contamination during operation. Physical sampling offers an accurate method for calibration of such sensors and verification of their operation over extended periods. In a recent river survey using a cabled robotic sensor payload, investigators successfully added on a prototypical actuated sample collection device in order to validate in-stream nitrate observations (Singh et al. 2006).

Extracting physical samples manually is laborious. This burden can be partially alleviated by systems that efficiently *trigger manual sampling*. By processing data as it is collected, sensing systems can notify users to collect samples at specific times and locations. Moreover, when humans are not present or cannot access a sample location, the system can guide a robotic sampler (described in detail in section 2) to one or more locations for automated collection of physical samples.

1.3 SHRINKING THE LAB TO A CHIP

As the broad range of needs for chemical and biological sensors suggests, future sensors with multi-element and chemical speciation capabilities are highly desirable. This so-called *lab-on-a-chip* (figure 1.4) technology is being realized in stages as developers ruggedize and miniaturize the packaging of traditional benchtop instruments, such as the ISUS nitrate sensor noted above. In addition to performance enhancement, this lab-on-a-chip approach may offer low power consumption to extend the deployment lifetime. The right scientific and economic incentives will accelerate the development of new detection methods. Techniques that are good candidates for investment include spectroscopy (e.g., ultraviolet, infrared, Raman, laser-induced breakdown, and X-ray), electrochemistry, radiochemistry, mass spectrometry, and fundamental analytical separation processes (e.g., liquid and gas chromatography). Expensive versions of some of these instruments exist in forms too bulky or fragile to deploy in the field. One significant long-term development need is to

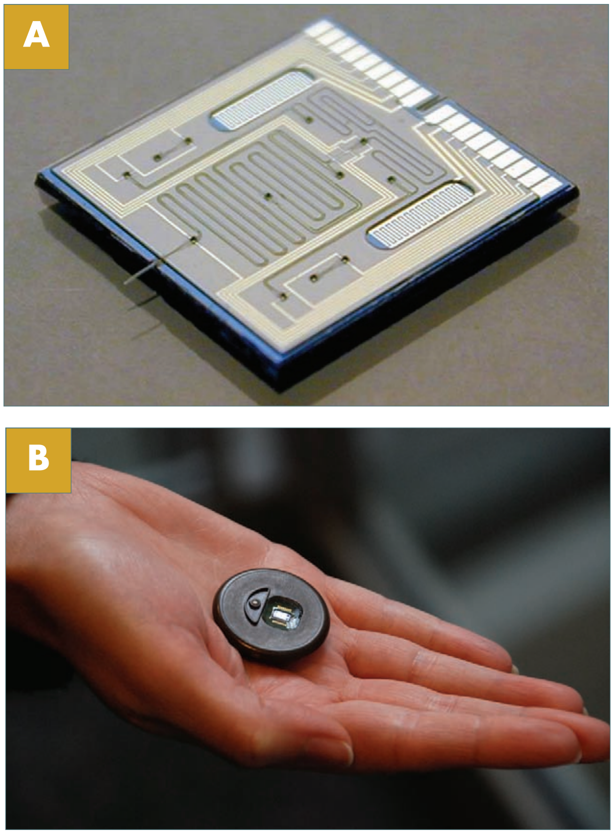

Figure 1.4 Examples of lab-on-a-chip sensors. (A) Lab-on-a-chip liquid chromatography sensor. Single 1 cm x 1cm chip contains pumps, flow sensor, electrodes, filters, and analysis columns. *Photo: J. Shih, CalTech.* (B) Water lab-on-a chip from WaterPOINT™ (hand shown for scale). Tests for 14 water quality elements in four minutes. *Photo: D. Rejeski, WWICS.*

leverage current lab-based microscale chemical separation techniques into the creation of field-capable chemical detectors, a move that will likely require targeted scientific and regulatory incentives.

1.4 MOVING FROM THE LAB TO THE FIELD TO DISTRIBUTED OBSERVATIONS

Many sensors are ready for laboratory applications but need additional development before they will be ready for field deployment in distributed systems. For a sensor that has not already been commercialized for field deployment (see figure 1.1), a significant amount of *in situ* testing is needed to determine (1) the useful range of environmental media in which it can operate, (2) how long it is operational in the field, (3) the optimal form factor (e.g., shape and size), and (4) the appropriate physical deployment method. For example, ISEs provide rapid sensing of pH and a large number of cationic and anionic species in laboratory applications. For the most part, however, they are generally considered less field-ready because they require frequent re-calibration and other maintenance procedures to minimize the effect of signal drift, weathering of electrode membrane materials, and reduction of membrane effectiveness due to chemical precipitation and biological fouling. Even after such developments, *in situ* testing of these types of sensors will be necessary to quantify signal variation as a result of sensor aging, weathering, biofouling, wet-dry cycling, and environmental influences (ACT 2006). In spite of their limitations, ISEs can be useful in short-term sampling campaigns, and with additional electrochemical and materials science research, their operational life span will likely increase significantly. Other engineering innovations (e.g., built-in redundancy) can further prepare the sensor for field deployment.

1.5 THE SYSTEM IS THE SENSOR

Environmental monitoring is often concerned not only with measuring the concentration of contaminants or pathogens, but also with capturing the rate of propagation, or flux, of these species within or between environmental media. Sensing systems can process data coming from many spatially distributed sensors to reveal information that no single sensor can provide. In other words, the system becomes the sensor. For instance, a simple collection of pressure transducers and electrical conductivity sensors will reveal the slope of the water table and distribution of salts in groundwater. The same collection of sensors configured in a network and integrated with a simple groundwater flow and transport model becomes a virtual sensor that can quantify the salt flux emanating from a source, such as a septic tank. As this networked sensing system experiences a sufficiently broad range of environmental conditions, it can become part of a larger-scale model that forecasts the transport and fate of emissions such as those emanating from a septic field. Development of virtual sensors such as the one described above in test beds can give rise to sensing systems that are tolerant to a greater range of errors and uncertainty, including calibration error, network communications loss, and uncertainty in the underlying environmental model structure and parameters.

2. DEPLOYMENT PLATFORMS

Recent advances in automated, wireless, real-time, *in situ* data collection and analysis have greatly enhanced the power and intelligence of environmental monitoring systems (NRC 2001). Data-logging devices have traditionally required a wired connection to access data—making real-time interaction with monitoring systems difficult or impossible, especially in remote areas. Thus, users often conclude lengthy and expensive monitoring activities only to discover that hardware failures resulted in missing or otherwise faulty measurements. Adding real-time feedback capabilities to monitoring systems allows the system to analyze, for example, the quality and quantity of data produced, and to repeat missing or faulty measurements shortly after they occur—while it is still possible to re-sample. These same feedback capabilities also make it possible for systems to process data from *in situ* sensors and to initiate "intelligent" actions, such as triggering the collection of physical samples, in response to observed environmental events. Such actions can occur *semi-autonomously* or *autonomously* (i.e., with little or no user intervention).

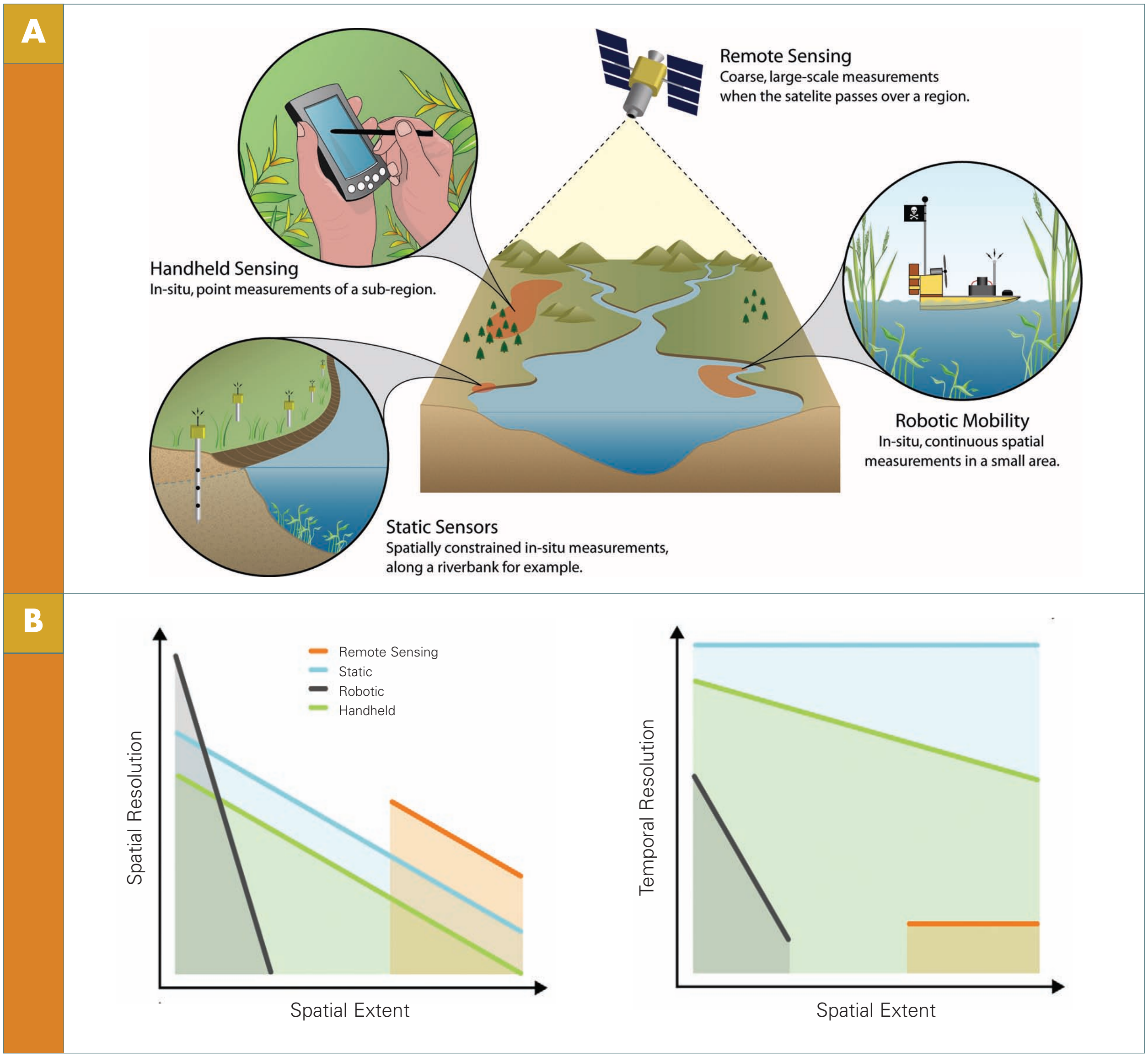

Figure 2.1 Comparison of classes of sensing system platforms (A) Relative spatial extent achievable by various sensing system platforms. *Illustration: J. Fisher, UC Merced.* (B) For a fixed cost (in time, labor, and equipment), the general relationship between spatial and temporal resolution and spatial extent for networked sensing systems, with remote sensing plotted as a familiar comparison. For each system type, the area under the line represents the range in which it can operate.

While traditional sampling platforms, such as data-loggers, can be connected to today's existing wireless infrastructure (e.g., cellular, WiFi) to communicate sensor data in real-time, most systems are large, power-hungry, and expensive. When even moderately dense sampling of a spatially-complex phenomenon is required, such an approach is limited by the cost of hardware, power, and communication infrastructure necessary to assemble the system. To overcome these obstacles, over the last decade, researchers building on advances in circuit miniaturization, have designed devices that integrate embedded low-power processors, wireless communication, and sensor interfaces (Bult et al. 1996, Kahn et al. 1999). When many of these devices are coupled to one or more sensor types they become nodes in an *embedded networked sensing system.* These systems enable real-time analysis and feedback even when operated in remote areas for extended periods.

2.1 MATCHING THE NETWORK WITH THE ENVIRONMENT

The impacts of environmental events, such as natural disasters and pollution from human activities, vary in time and space. They can occur rapidly across relatively small areas (e.g., sewage spills) or gradually across large areas (e.g., eutrophication of coastal regions). Conversely, events can occur gradually across small areas (e.g., storage tank leaks) or rapidly across large areas (e.g., hurricanes). Depending on one's objectives, the approach to investigating or monitoring the effects of such events may require sampling more or less densely *in space* across the area of interest or more or less densely *in time* during the course of the investigation. The different dimensions of spatial and temporal variation (i.e., extent and density) in the environment help determine the most appropriate sensing system to use for a given situation.

Since the creation of the first embedded networked sensing system, the technology and approaches to distributed sensing have diversified. Systems now exist that are tuned, based on relevant spatial and temporal variation, to reveal different types of environmental phenomena.

2.2 SENSING SYSTEM DEPLOYMENT CLASSES

Three new classes of embedded sensing systems can be used separately or in combination to investigate a great deal of the environmental variation encountered in natural and constructed systems: **(1) static sensing systems, (2) mobile robotic sensing systems,** and **(3) mobile handheld sensing systems** (figure 2.1). Selecting an appropriate sensing system or combination of systems depends on the characteristics of the environment such as the size of the area of interest and the degree of variation in the phenomena of interest. For instance, different sensing systems are designed to operate over a range of areas (spatial extent) and at different resolutions in time and space. In general, there is a trade off between the area that can be covered by a system and the number of measurement points that can be established in the area (spatial resolution). Systems designed for large areas generally cannot sample as many points in that area as can systems designed for smaller areas. Likewise, systems are limited in the number of measurements they can make in a given period (temporal resolution). For some systems, this limit varies with the spatial extent of the area under investigation (e.g., if a robotic sensor is moving over a large area, it cannot return to the same place to make measurements as often as it could if the coverage area were smaller). Figure 2.1 presents a rough generalization of these relationships, although there may be special cases that do not follow these guidelines. The following sections discuss these specific sensing system deployment classes in greater detail.

Static Sensing Systems

In static sensing systems, sensor nodes are deployed and remain fixed in space during the measurement period. Static deployments tend to live for several months or years because a significant amount of effort (often on the order of several days to a week) is invested in the initial set up. Hardware costs often limit the number of sensor nodes available for a

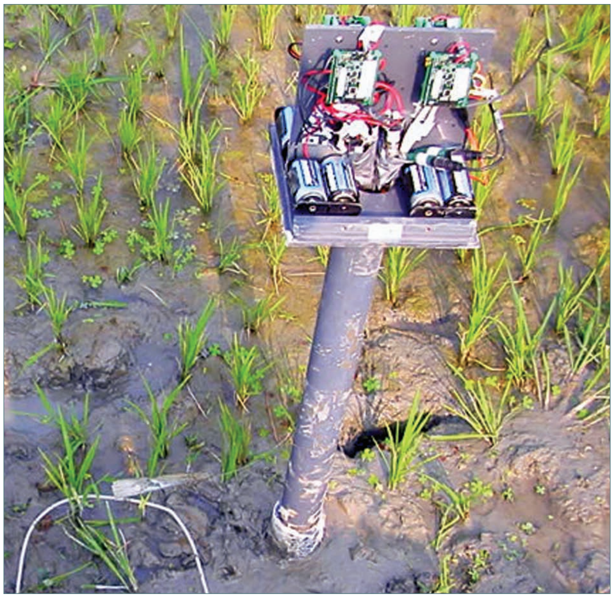

Figure 2.2 Static soil sensor pylon deployed in a Bangladesh Rice Paddy. Rugged PVC enclosures protect communication, power, and computation hardware. Sensors (buried underground) and enclosure cover are not shown. *Photo: N. Ramanathan, UCLA.*

specific study. Thus, a trade-off usually exists between the area that can be covered by sensors and the sampling density that can be achieved in that area. Because each sensor is dedicated to a particular location and continuously available for sampling, high-temporal frequency measurements are possible (figure 2.2).

Static sensing systems are well suited to environmental monitoring. One common application of static systems is to map micro-climate conditions. Typically, static sensor nodes are deployed over an area of several square kilometers with spacings on the order of tens of meters. Recording measurements every several minutes is usually sufficient to capture climatic variation over the course of several months. From 2002 to 2003, in a now famous example of a static sensing system deployment, a group of engineers and scientists deployed approximately 100 sets of temperature, humidity and passive infrared sensors on Great Duck Island, off the coast of Maine, to study how micro-climate conditions affect nesting behavior of Leach's Storm Petrels (Szewczyk et al. 2004). Since 2003, similar dense spatial and temporal data has been collected from a static system of micro-climate sensors installed in the James Reserve in the California's San Jacinto Mountains (Guy et al. 2006).

Distributed, wireless static sensors are being developed and used to create systems that essentially control themselves, with little or no human intervention. One such sensor system, designed by Advanced Sensor Technology, Inc., employs a wireless mesh network used to control irrigation on golf courses (figure 2.3). Sensors deployed at various points across a golf course measure soil moisture, temperature, and salinity, and transmit that information back to a central control node (Kevan 2006). Software then interprets this data and communicates messages to control irrigation. This type of self-regulating system helps prevent unnecessary or excessive water use for irrigation.

Among the various classes of sensing systems, static systems use relatively simple hardware platforms and require the least user intervention of the three platforms described. However, static systems can be impractical in situations where there is complex spatial variation because the need to replicate sensors and nodes at high density becomes cost prohibitive. Mobile robotic sensing systems are better suited to such situations.

Mobile Robotic Sensing Systems

In robotic sensing systems, one or more sensors move to the sampling locations of interest (figure 2.4). Motors and other devices, which are controlled either manually by a person or autonomously by a computer, generate the sensor motion. These mobile systems make it possible for fewer sensors to make relatively dense measurements over constrained areas, thereby resolving complex or spatially-dynamic environmental variation (an impractical task with static systems). Robotic systems range from permanent installations, which can operate over long periods and require several days to set up, to rapidly deployable systems, which only require hours to set up and allow users to move systems to multiple locations during an investigation. Another consideration in choosing a sensing system is that robotic systems generally have greater power requirements and more complex hardware than do their static counterparts.

The robots in sensing systems take different forms. For instance, vehicles (e.g., boats) can transport sensors to sampling locations (Dhariwal et al. 2006; ASL 2006; Monterey Bay 2006; Edgington and Davis 2004), or support structures (e.g., cables and tracks) can provide fixed paths or transects along which a sensor can travel (Stern et al. in press; Batalin et al. 2005). Fixed devices such as buoys allow for vertical profiling of a water body (Doherty et al. 1999; Reynolds-Fleming et al. 2002). Autonomous underwater vehicles (AUVs), which have been used extensively by the oceanographic community and recently in lakes and river systems, can be programmed to follow prescribed courses (Laval et al. 2000; Yu et al. 2002) or to sample adaptively; for example, to track a contaminant plume (Ogren et al. 2004; Farrell et al. 2005; Sukhatme et al. in press). Robotic systems allow for movement in multiple dimensions, and thus provide access to large volumes of water, air, and soil. In one recent example, a cabled robot was deployed over a river at locations upstream and downstream of a confluence zone (the point where two rivers join) (Harmon et al. in press). The system then sampled regularly-spaced vertical profiles at regularly-spaced horizontal intervals across the river (figure 2.4). The resulting data, which amount to a cross-sectional profile of the river, revealed detailed information about the concentration of chemicals flowing through each branch of the river and how those chemicals mix in the area downstream from the confluence.

The dense spatial coverage of robotic systems may come with a trade-off against sampling frequency since the time required to return to any given point depends on the number of other points to be sampled. In such cases, robotic nodes can incorporate *multi-scale* or *adaptive sampling techniques* (see section 2.3 below) to more intelligently direct the node to focus on regions requiring additional spatial or temporal sampling density. For example, data from static sensors beneath buoys in a lake were used to direct a boat on the surface to collect data at intermediate points to construct a time-varying three-dimensional map of chloro-

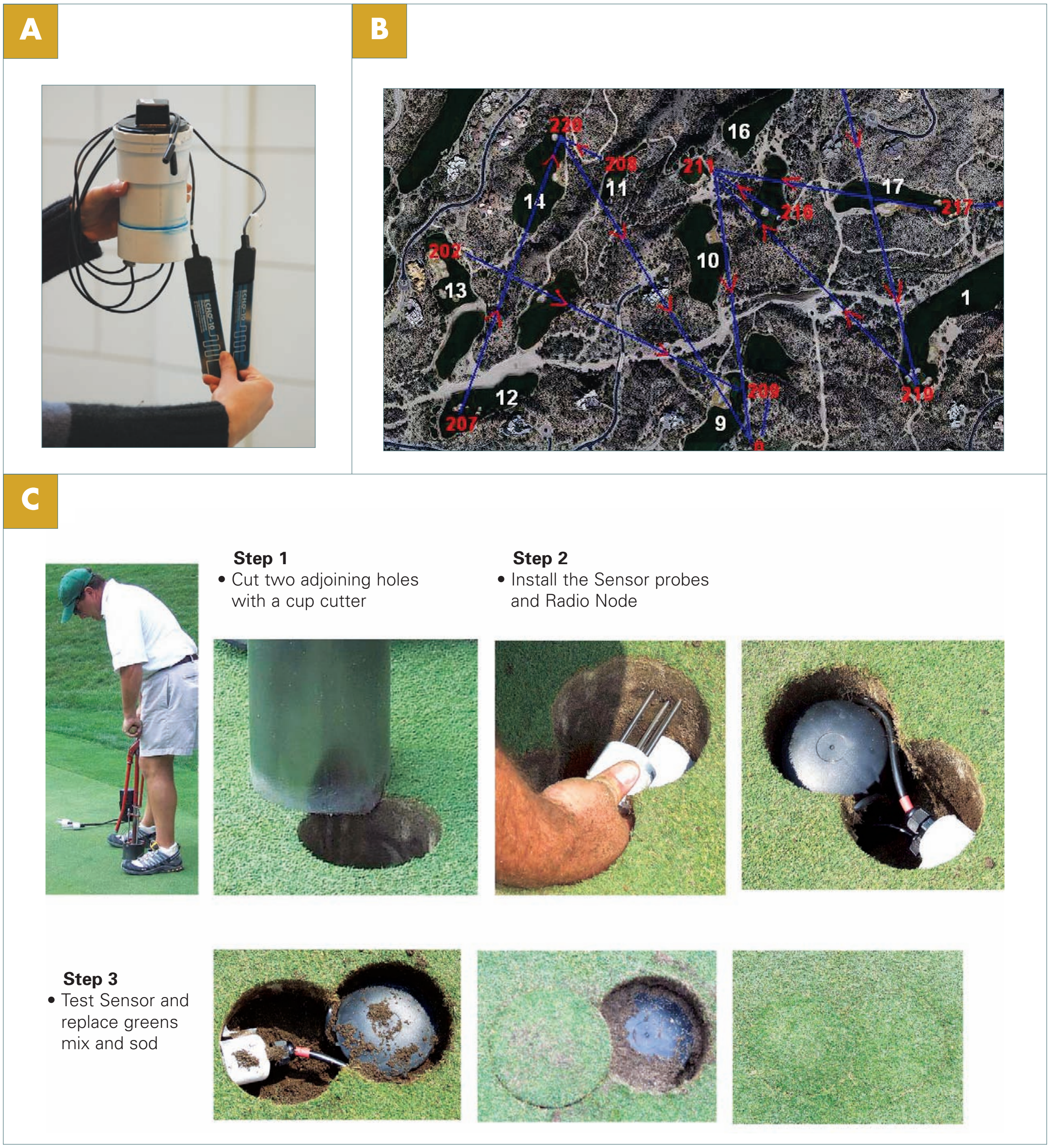

Figure 2.3 Example of static sensors for self-regulating systems. (A) Node with sensor probes for in-ground deployment. *Photo: D. Rejeski, WWICS.* (B) Communication across golf course mesh network. *Image: Advanced Sensor Technology, Inc.* (C) Sensors and sensor node installation process on a golf course. *Image: Advanced Sensor Technology, Inc.*

phyll concentration (an indicator of phytoplankton) in the lake (Batalin et al. 2005). Also, in recent work, researchers are designing robotic cameras that move along the inside of clear tubes buried in the soil and take pictures of the fine structural details of plant roots. These images indicate how plant roots change over time in response to environmental changes, which are measured by static sensing systems above the soil (Hamilton et al. in press). In each of these cases, high-resolution scans of the environment have revealed complex and highly variable spatial information of the system under study.

Mobile Handheld Sensing Systems

Extremely powerful handheld computers, which, like the sensing systems described above, incorporate low-power processors, wireless communication capabilities, and flexi-

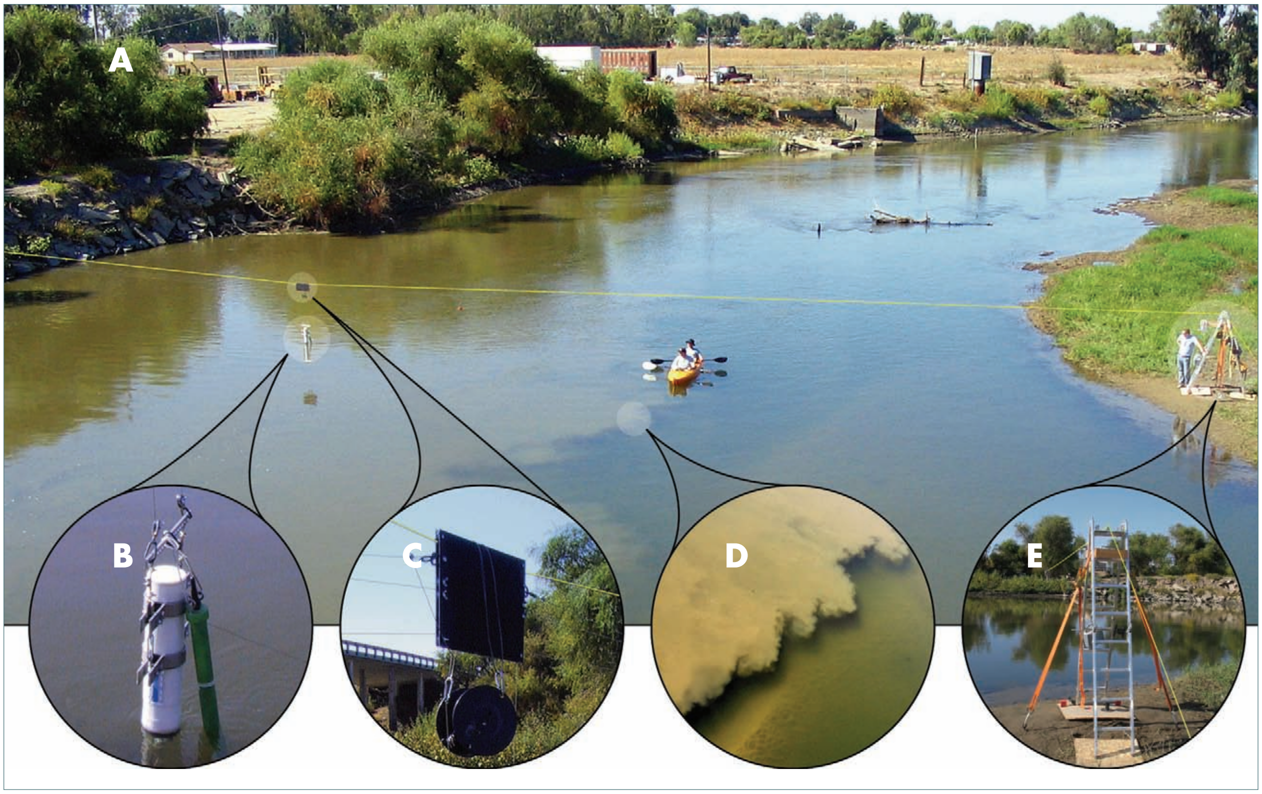

Figure 2.4 Example of a robotic sensing system. (A) Actuated shuttle suspended from an overhead cable move perpendicularly across a river. The shuttle carries a payload of water quality sensors, which can move vertically through the water column. This system determines detailed profiles of various parameters across the river from which mass flux can be calculated. (B) Detail view of sensor payload. (C) Detail view of shuttle. (D) Detail view of mixing zone downstream of the confluence of two rivers. (E) Detail view of end mounting system.
Photos: J. Fisher, UC Merced.

ble sensor interfaces, are widely used in personal and industrial applications. These personal data assistants (PDAs) and cellular telephones are merging into so-called smart phones, which are programmable and increasingly contain integrated sensors, such as cameras, microphones, and global positioning satellite (GPS) receivers. To date, environmental monitoring efforts have incorporated these sophisticated devices in basic ways. Over time, they will create, in effect, a new type of mobile sensing system.

Although many environmental data sets are still initially recorded by hand on paper before being encoded digitally, rugged handheld computers are increasingly being used as a primary data collection tool. The use of such devices eliminates a manual (and often error-prone) paper-to-digital encoding step and also improves data quality by (1) prompting a user to enter both data and metadata according to standard protocols; (2) automating certain routine tasks (e.g., time and date stamping); (3) checking data validity (e.g., using drop-down menus or pre-determined rules); (4) automatically geo-referencing data; (5) enabling users to record contextual information, such as photographs and voice annotations, using integrated cameras and microphones; and (6) uploading data regularly and automatically via wireless connections (e.g., cellular or WiFi) to central data stores.

Built-in wireless connectivity and local data processing create opportunities for handheld computers to provide real-time feedback to users in the field. By processing data retrieved from remote databases or from local sensing systems, users can be instructed to collect data more efficiently. For example, a user in the field could use river transport models accessed via the Internet to analyze locally collected data and direct subsequent data acquisition. Similarly, a static or robotic sensing system in communication with a handheld computer could trigger a human to manually deploy a sensor that cannot be embedded in the environment or to record simple observations. The system could then process the result, and if it does not meet certain quality standards, instruct the user to re-sample. Such interactions between the people collecting data in the field and local and remote computer resources stand to be a powerful new tool for improving the efficiency and quality of environmental data collection.

Great potential also exists to connect handheld computers with sensors. Already, cameras, microphones, accelerometers, and GPS receivers are integrated into devices. The information returned by those simple sensors can be combined and analyzed through local data processing. For instance, the handheld computer can automatically read and record images of printed characters or barcodes to automate certain types of data collection. Moreover, standalone sensors are increasingly being developed with standard wireless interfaces (e.g., Bluetooth) which can connect to handheld computers to allow people to automatically collect data from sensors installed in the field, or to carry wireless sensors to sampling locations. By acting as data gathering and communication devices, handheld computers become nodes in a mobile, networked sensing system.

Aside from improving the efficiency and quality of data collection, handheld computers can be distributed to many people who take part in coordinated data collection efforts. By leveraging the processing, connectivity, and sensing capabilities of current and next-generation handheld computers, diverse, distributed human-powered sensing systems can be created at local, regional, continental, and global scales. Such *participatory sensing networks* (Srivastava et al. 2006) will give rise to an unprecedented amount and variety of data about the environment and human activity.

In the hands of trained environmental professionals, as well as citizens, these distributed, mobile sensing systems can detect environmental variation at scales unattainable by their robotic and static counterparts. Communities around the world already monitor local rivers, streams, estuaries and other water bodies as part of World Water Monitoring Day, a program to increase public awareness and involvement in protecting water resources. Since its inception in 2002, more than 80,000 people in 50 countries have participated by measuring water quality parameters such as pH, dissolved oxygen, and temperature using kits received in the mail and by uploading manually entered data to a central database (WWMD 2006). Soon these same communities may be able to harness sensors integrated in their cell phones to monitor water and air quality all year long, with data continually uploaded in real-time. Systems receiving the data could respond by acknowledging receipt and even directing users to nearby locations that lack measurements.

Before this vision of a mobile, handheld, networked sensing system is achieved, the issue of trust must be addressed. Why should people believe data collected in such a distributed manner? The value of handheld measurements—or any measurement—depends on answering this issue of trust at all levels. Current research is addressing how the design of network infrastructure can attest to the credibility of data and its context (e.g., location or time of collection), as well as how to design local data validation techniques that identify and flag suspicious or faulty data and make use of redundant measurements to increase the quality of data (see section 2.4 below).

2.3 ADAPTIVE SAMPLING AND MULTI-SCALE SYSTEMS IMPROVE COVERAGE

Adaptive Sampling

Ideally, sensors could continuously monitor every point of interest in an area. In practice, however, resource limitations (e.g., number of sensors or availability of power) prevent continuous and complete coverage. In such cases, *adaptive sampling techniques* can help allocate sensor resources as efficiently as possible by controlling where and when they make measurements (Rahimi et al. 2004; Rahimi et al. 2005; Singh et al. 2006). One approach to adaptive sampling is to allocate more sampling resources to areas with higher spatial or temporal variation. For example, if temperature varies more around the edge of a lake than in the middle (for instance, due to sharper depth gradients), then a computer running an adaptive sampling routine would guide a robotic temperature sensor (e.g., attached to a boat) to spend more time—and thus collect more samples—near the edge of the lake. In a static sensing system, adaptive sampling can be used to dynamically vary the sampling rate of different sensors so that they collect samples more frequently during periods when values are changing most rapidly. This saves power because sampling occurs less frequently overall. The systems can learn when rapid changes are likely to occur based on statistical analysis of prior measurements or models of the phenomenon under investigation and continually refine and update the routine to operate more efficiently.

Multi-scale Systems

Often phenomena of interest vary at multiple scales. In such cases, *multi-scale systems*, consisting of combinations of sensing platforms, acting in concert, will be needed to capture complex phenomena. For example, a sparsely deployed set of static sensors might reveal several relatively small areas of interest to sample at high resolution with a robotic transect. The resulting high-resolution information, in turn, could reveal a few still smaller areas in which physical samples are required for intense laboratory analysis. A robot or human could return only to those locations whereupon an actuator could automatically collect the samples. Such multi-scale systems introduce a hierarchy of sensors and actuators to provide a unique capability, in which one sensing tier may rely upon another to guide it—thereby most effectively assigning sensing resources (figure 2.5). Since resources are always finite and high-resolution measurements are expensive, sensing systems designed to exploit this multi-level approach can save time and money.

Currently, remote sensing (airborne and satellite) is used to collect data over large areas but only at relatively low spatial and temporal resolution (although resolution has improved and will continue to do so). Thus, when interacting with static, robotic, or handheld systems, remote sensing systems also represent a tier in a multi-scale sampling approach. By acquiring large-scale, low resolution views of the environment, remote sensing systems can guide the geographic deployment of multi-scale sensing systems and, ultimately, interact with sensing systems to automatically guide data collection in real time. This integration will not only enable more thorough ground-truthing of the remotely sensed information but will also serve as a valuable layer of information in novel environmental observations.

2.4 ROBUST SYSTEMS AND INTELLIGENT POWER CONSUMPTION INCREASE SYSTEM LIFETIME

It is critical to design a system to meet the lifetime requirements of an application. There are two major issues that limit the lifetime of a distributed sensing system: constrained power supplies, and faults impacting communication or sensing hardware. These issues cut across all sensing systems platforms, and similar techniques can often be employed for different platforms to address these limitations.

Power Consumption. Many deployment environments have limited or no power infrastructure, and sensing systems must thus rely on battery and/or solar-panel power. In such situations, reducing power consumption is one of the primary ways to extend the life of a system. Systems conserve power by minimizing power-hungry operations such as activating a sensor and recording the value from it, and sending or receiving a wireless signal to neighboring nodes. As described above, adaptive sampling techniques can be used to minimize sampling by focusing

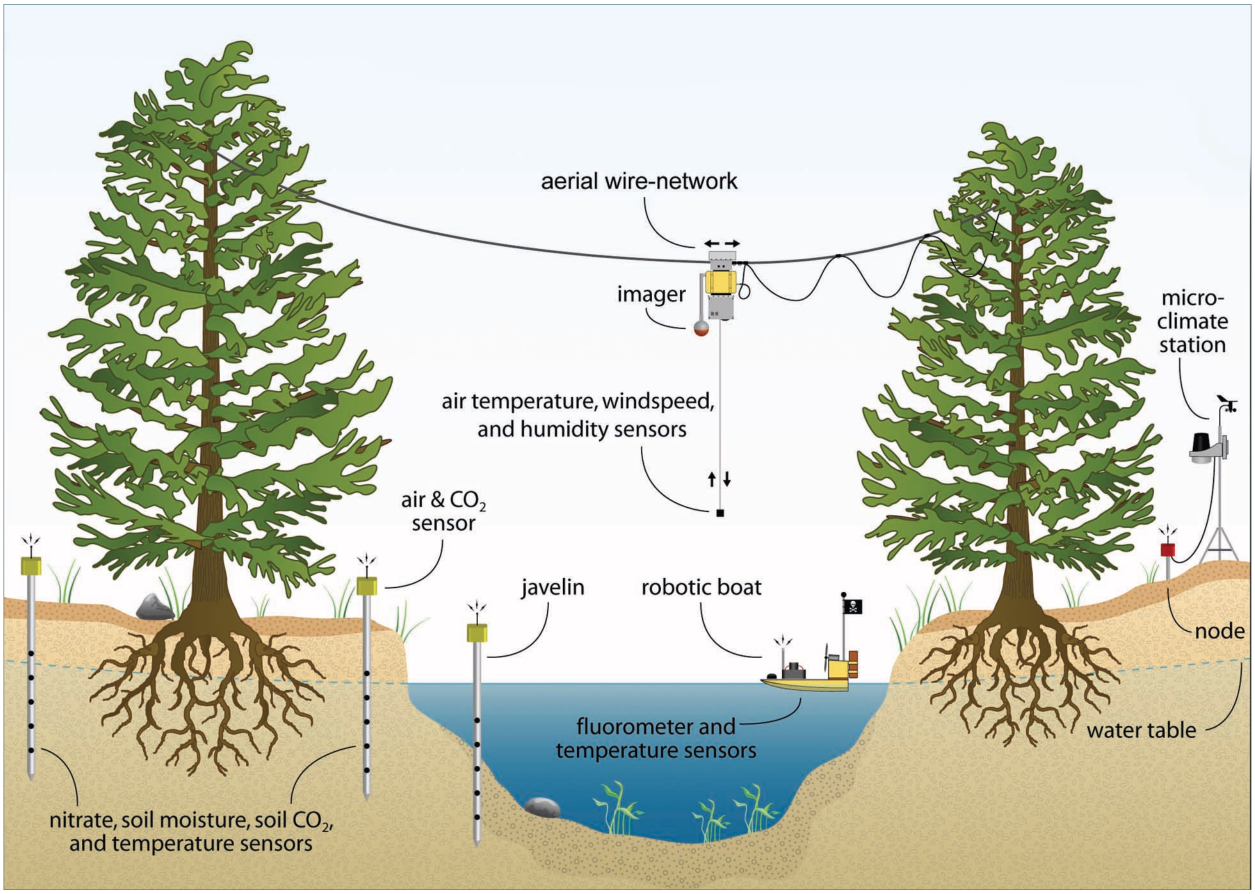

Figure 2.5 Illustration of a multi-scale sensing system. Multi-scale sensing systems can share data among different platforms for efficient use of sensing resources. For example, low resolution images mounted on a robot moving between trees can communicate measurements to static or mobile sensors below to identify areas requiring higher resolution measurements. *Illustration: J. Fisher, UC Merced.*

resources only in areas of interest. There are many approaches to reducing power, each with their own advantages and disadvantages, but not all techniques are appropriate for all applications and platforms. Application requirements often guide or restrict the choice of power saving techniques. For example, an application may require a regularly spaced sampling interval in space and time, thus adaptive sampling could not be used. Similarly, temporal variability in an environment may dictate a high sampling frequency, making it difficult to limit wireless communication and sensor sampling.

Robust System Design. In addition to running out of power, there are many other potential issues in the life cycle of a sensing system that can shorten its lifetime. Sensor failures, drift, and bio-fouling can interfere with the generation of data or the data quality. Robotic hardware failures and environmental hazards (e.g., falling branches that destroy devices or interfere with wireless communication) can negatively impact the delivery of data or the data quantity. In addition, extreme weather, curious animals, and ambient conditions contribute to the general wear and tear of system hardware. Systems that effectively handle such assaults are called robust. To minimize user intervention, robustness to such issues should be designed and built into the sensing system at all levels.

System tools that aid in detecting and diagnosing faults are available and should be deployed as part of sensing systems using various techniques. One common technique involves deploying duplicate sensors and looking for differences in their outputs as a clue to sensor failure. In addition to hardware redundancy, analytical redundancy in the form of physical models that mathematically define expected behavior of a phenomenon can be used in conjunction with sensor data in order to identify sensors that do not behave as expected. Tools can also rely on partial redundancy in space and time to identify faulty sensors: measurements from neighboring sensors or from past samples are often similar and can be compared with one another. Once a faulty or missing measurement has been detected, tools exist to diagnose problems and help users fix them.

Robustness to faults impacting data quality and quantity should also be taken into account when designing a study. For example, the particular environment in which a study takes place should be documented to aid in subsequent data analysis. Additional sensors and handheld measurements can be used to record such metadata, which is useful in documenting the context. For example, extreme weather conditions, such as snow, may impact the data collected during an entire deployment, but can be easily documented with data from a weather station. Recording such information may seem obvious but must not be forgotten, especially during autonomous deployments, so that data can be analyzed in the proper context and faults can be identified with confidence.

Some robustness issues are specific to the deployment and sensor characteristics. For example, ISEs provide affordable *in situ* measurements of some water quality parameters. While these sensors are currently available for embedded sensing, they require frequent maintenance and calibration (as described in section 1) and thus are better deployed for shorter periods of time. For applications that require deploying these sensors for longer than several days, a human attendant is required to frequently visit the sensors to provide maintenance and calibration. Future research should focus on designing more autonomous sensing systems that can detect, diagnose, and even fix such problems with little or no user intervention. For example, a tool detecting that an ISE requires re-calibration could inject a known solution to the tip of a sensor through a pre-attached tube and record the resulting measurements. While not taking the place of laboratory calibration, such *in situ* calibrations could extend the time between laboratory calibrations.

3. THE DATA LIFE CYCLE

3.1 UNIQUE CHALLENGES FOR SENSING SYSTEMS

As the previous sections illustrate, embedded sensing can involve a mix of observations with inherently different characteristics. For instance, it is common for systems to include multiple sensors, each with a different form of sensory perception or *modality*. In many environmental science applications, physical measurements are paired with either chemical properties or indicators of biological activity or both. While mathematical or statistical models of environmental phenomena often rely on a mix of such measurements, there can be practical or operational uses for this diversity as well. For example, simple correlations between modalities can be used to develop sampling strategies that employ low-cost, fast-responding sensors for routine monitoring and activate higher-cost sensors either less frequently or in response to identified "events." This is one example of autonomous *actuation* on the part of the system.

In addition to employing multiple modalities, sensing systems can record data at *multiple scales*. For example, while remote sensing can provide a wide view of environmental phenomena, it is often difficult or impossible to extract the kind of physical, chemical or biological data required for environmental applications, including regulatory actions. Instead, remote sensing can be used to highlight regions of interest and, in turn, trigger more focused data collection. When used in combination with robotic systems, embedded sensing can achieve a spatial resolution not possible with collections of statically deployed sensors. This is another example of autonomous actuation, but one that is much more complex than the simple duty-cycling of sensors mentioned in the previous paragraph.

The data returned by multi-scale, multi-modal actuated systems are complex and pose a host of challenges for the person interpreting them. First, the simple act of fusing these sources for use in modeling can involve more than a simple database "merge." Instead it might require more complex statistical processing. Secondly, uncertainty inherent in all sensors and, when applicable, associated with their movement must also be incorporated into models and analyses in order to track how uncertainty propagates through the system. However, even with all these sources of uncertainty, it is reasonable to expect that by understanding the correlations between modalities and scales, it is possible to design sensing systems to ease the burden of analysis downstream.

3.2 THE LIFE CYCLE OF DATA FROM EMBEDDED OBSERVATIONAL SYSTEMS

To help address some of the challenges facing sensing system effectiveness and interpretation, it is useful to examine the "life cycle" of data in a sensing system by focusing on three distinct phases: design and deployment of the observing system; operation and monitoring; and analysis, modeling and data sharing (figure 3.1).

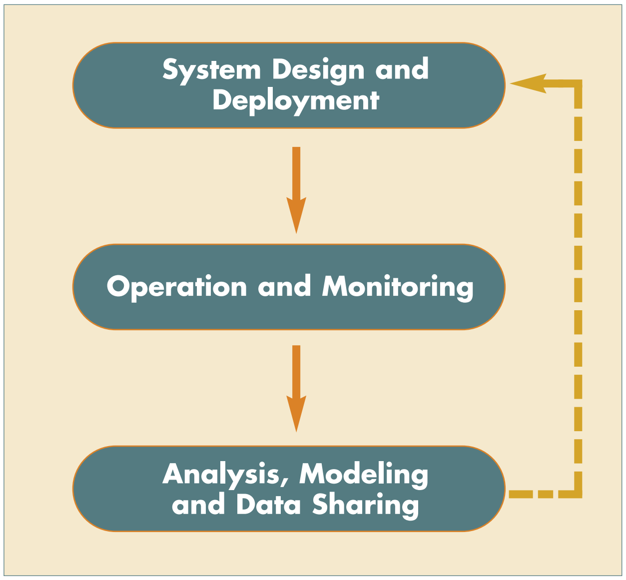

Figure 3.1 Life cycle of data from embedded observational systems. First data are used to locate sensors, then data are necessary to monitor the system health during the observation period, finally the data are analyzed and shared as information about the environmental phenomenon of interest. Each deployment provides information about how to design subsequent investigations using embedded systems (dashed line).

Design and Deployment

Many early visions of networked sensing systems ignored deployment design completely, suggesting that sensor nodes should be simply scattered in a region. While this is perhaps appropriate when deploying thousands of sensors, current sensing practice recognizes that it is rarely possible to deploy enough sensors in this manner to achieve adequate spatial coverage. Thus, there is still a benefit to well-designed deployments.

Designing an observing system requires, not only identifying the sensors of interest, but also placing them carefully (formally a problem of experimental design), determining the sampling regimen (which may adapt to the underlying phenomena in some way), and coordinating data collection by the system (possibly involving actuation logic or the "choreography" of robots or humans). These choices can be informed by other streams of data, often created and maintained by external organizations; they can also benefit from staged or sequential design approaches, in which small deployments are used to bootstrap larger, more complex installations. Being able to discover relevant data sources nearby, merge streams of data, and work with preliminary mathematical or statistical models is a crucial part of the sampling design question.

A mix of techniques, including informal experimental design, optimal design and even Bayesian design, can help to determine appropriate placement of sensor nodes. Data processing within the sensing system weaves data into the underlying logic and algorithms for coordination, an interaction that is most effective when scripted by a user. This process, in effect, asks for a mixing of subject-area models (how the user encapsulates knowledge of the environment) with data processing and actuation (how the network comes to know the environment). In part, these are questions of:

- Data fusion and management: Through what mechanisms are streams of data combined? Where do we place subject-area models in the network?
- Data integrity: How do we ensure that the sensors are properly coupled with the environment? What redundancy can we put in place to identify faults?
- Data quality: Which cluster of sensors will remain calibrated the longest?

There are currently a number of research efforts that attempt to provide users of sensing systems with design tools. Many employ an iterative scheme that sequentially alters deployments to capture spatial variability or some other metric of interest. Maps, local images, and other data sources (e.g., climate records) are used to inform a step-wise sampling strategy.

As mentioned in section 2, sometimes long-lived autonomous systems are impractical or unnecessary. When an environment changes slowly and can be characterized quickly, rapidly deployed sensing systems are effective. Such systems are often sensor-intensive, operate for a short period of time, and require fast set-up, calibration, and take down. In such cases, it is useful to not only be able to store all the data collected during the short period for later analysis but also to have access to all the data in the field to support on-the-fly design, calibration, and system monitoring. These semi-autonomous systems can benefit from other network tools such as handheld computers that allow users to probe the state of the systems to ensure that they are functioning properly.

Operation and Monitoring

Once deployed, data management and analysis remain important elements of the overall system. For instance, a decision about where data are to reside and in what form must be made explicitly. This includes making a determination about whether there should be a central repository, and if not, how to discover and link disparate data stores. Further, because local data processing is possible, users can decide to collect, fuse, and store data at regular intervals (as is done in most conventional systems) or to program the system such that it reports and stores data when events of interest occur. The latter option is attractive when the cost of transmitting and storing data is higher than the cost of computation on small sensor platforms. If one decides that the system need only report and store data when an event occurs (i.e., it speaks only when necessary), methods for routinely assessing and ensuring the health of the system during its "quiet" phases are critical (i.e., systems must be robust).

Therefore, as discussed in section 2, tools for identifying communication faults, which, in effect, cast the system as a *witness* to data transmission can assist with data issues for active systems. In more recent work, this idea of a witness has been extended to larger issues of data quality and calibration. In this case, the system collects a "context stamp" at fixed intervals, a kind of heartbeat that provides a regular view of both the sensor and the overall system. Various frameworks, such as Bayesian models, fraud-detection techniques, and reputation assessment, exist for identifying when sensors are behaving "as usual" and when they have significant quality or integrity issues. Some of these techniques are currently in a research and development phase. Another important area of research surrounds data security for sensing systems, which are susceptible to security breaches similar to those that affect other computer networks. Data quality is a central concern for any sensing system, but even more important when the resulting data are used in regulatory situations.

If a system error, or fault, is detected, most fixes involve a human operator either on-site or at a remote computer terminal. As with fraud detection approaches, operators are alerted to a problem, such as a calibration or data quality issue, and can take action by, for instance, visiting the location of the fault or tasking robotic systems to address the problem.

Handheld sensing systems are another tool available during the operational phase of the data life cycle. By collecting primary data from sensors that interface with the handheld computer and by providing access to data collected by other sensing systems, to data streams originating outside the system, and to other nearby observational resources (including robotic elements and other users), these systems can provide a user with contextual information in the field, which can be used to inform inevitable on-the-spot decisions related to the data collection effort.

Analysis, Modeling and Data Sharing

When sensors are deployed and the network is functioning properly, data analysis becomes important. Tools for search and discovery of sensor data are critical to data fusion tasks. As with any quantitative measurement system, data analysis must include considerations of how uncertainty propagates through these distributed, networked systems from design choices to routine operation. Calibration and actuation each impose uncertainties. When actuation is involved, the uncertainties can increase because with actuation the initial decision to act can itself be data-driven. An important data sharing issue is adherence to standard data and metadata formats, which are necessary if data will be shared between different organizations and possibly different disciplines. Standardization also remains important for derived data products (i.e., the results of modeling, analysis or even simple aggregation). These issues are not necessarily unique to distributed, networked sensing systems; however, because datasets from such systems are generally large and heterogeneous, they are particularly complex. For example, adaptive sampling algorithms can help observers discover hidden phenomena but they may not produce observations on regular grids—a situation that makes downstream modeling more difficult. Another data analysis challenge involves communicating the complex results of data analysis in terms that are meaningful to a variety of audiences, from the scientific community to policymakers and the public.

The last decade has seen geographic information systems (GIS) become increasingly accessible. Today vast amounts of data are displayed, organized, and searched through map interfaces and many sophisticated interfaces, such as GoogleEarth, are accessible to large portions of the public. The incorporation of maps with real-time data feeds is an important component of visualization for sensing system data. The ESRI tool ArcHydro is a good example of a platform that marries mapping, modeling, and live data to produce dynamic flood predictions. This is an area likely to see continued innovation and tools to simplify geography-based visualization and even allow for interactive modeling and prediction. It is through mapping that complex environmental information can be usefully communicated to the general public. Data frameworks for sensing systems can even be developed to support data contributions by the public and communication of the public's impressions and analysis of the information.

4. USE-CASE SCENARIOS

Embedded networked sensing systems are a new and rapidly evolving technology that enables novel approaches to the investigation of environmental challenges. These systems offer advances in the ability to quantify environmental problems and develop a mechanistic understanding of their causes and controls—two requirements for effective regulation and mitigation.

As described in section 2, different sensing systems are suited to investigations of environmental issues with different spatial and temporal characteristics, such as the geographic extent of the environment of interest, the number of measurement points needed, and the time course of the issue of interest. Below, four scenarios that cover current environmental challenges with different spatial and temporal characteristics are presented along with a description of how state of the art sensing systems can be used to understand and quantify the problem, a key step in effective environmental stewardship.

4.1 SEPTIC SYSTEMS

A significant number of households and businesses in the United States use septic systems to treat and discharge wastewater. Septic systems are designed to adequately attenuate the release of dissolved and suspended domestic waste components into the subsurface environment. This means that in the ideal septic system, contaminant release, or flux, from the septic tank is balanced by reactive and dispersive forces that reduce contaminant concentrations to acceptable levels before the flow of water from a system reaches a viable water supply or sensitive aquatic habitat. Many systems are more than 30 years old and an estimated 10 to 20 percent are malfunctioning (EPA 2005). Because septic systems consist of multiple, distributed pollution sources, they are difficult to thoroughly monitor and regulate.

Malfunctioning septic systems are a nationwide problem. However, malfunction of any particular system is unpredictable, and, when one occurs, the detrimental effects are relatively slow to accumulate. Thus, while there are millions of potential measurement points, data from each point does not need to be reported immediately in order to implement effective corrective actions. These spatial and temporal characteristics suggest that a practical approach to monitoring and managing existing septic systems involves a handheld sensing system or a combination of handheld and static sensing systems.

In areas with municipally supplied water, municipal employees who visit homes or businesses to read water meters could conduct the monitoring of septic systems. Three approaches are possible depending on the desired level of information and the resources available for sensing hardware. One approach that minimizes hardware costs involves a technician carrying sensors that interface with a PDA-type device and making point measurements in the septic field at the time of a meter-reading visit.

In a more thorough approach, which involves more dedicated hardware, technicians can deploy small static sensing systems consisting of multiple sensors in an area containing multiple septic systems and record data during one or more visit cycles. This approach allows sensors to integrate measures over time and would provide more detailed information about the composition of wastewater. Technicians could then remove and redeploy the static sensing system at different locations in an ongoing monitoring cycle.

Finally, if hardware can be dedicated to certain geographic regions such as residential subdivisions, a static system can be employed to monitor nearby water bodies (e.g., coastal regions, lakes, and rivers) and subsurface areas for signatures of malfunctioning septic systems. In this case, sensors could be deployed at and around collecting channels downstream from several septic fields, thereby integrating over relatively large areas. The sensing system can be programmed to notify officials if a problem is detected, at which time a more intensive investigation of the source of the problems can be initiated.

The other key consideration pertaining to the use of embedded sensing systems to monitor septic systems is the availability of appropriate sensors. Common water quality contaminants emanating from septic systems include pathogenic microorganisms, salts, nitrogen and phosphorous species, and dissolved organic carbon (or biochemical oxygen demand). With improper disposal, the realm of contaminants also includes metals, household solvents, and petroleum hydrocarbons. Field-ready sensors are available for several of the parameters, including electrical conductivity sensors, which can delineate the spatiotemporal TDS distribution in a leach field, and water level sensors, which can quantify the hydraulic gradient in a septic field. Static sensing systems can use the information it collects about the hydraulic gradient and an estimate of the soil hydraulic properties to quantify the attenuation rate of TDS and, more importantly, to identify undesirable changes in the rate and notify users when the septic tank requires servicing. Additional sensors can be incorporated as they become field-ready.

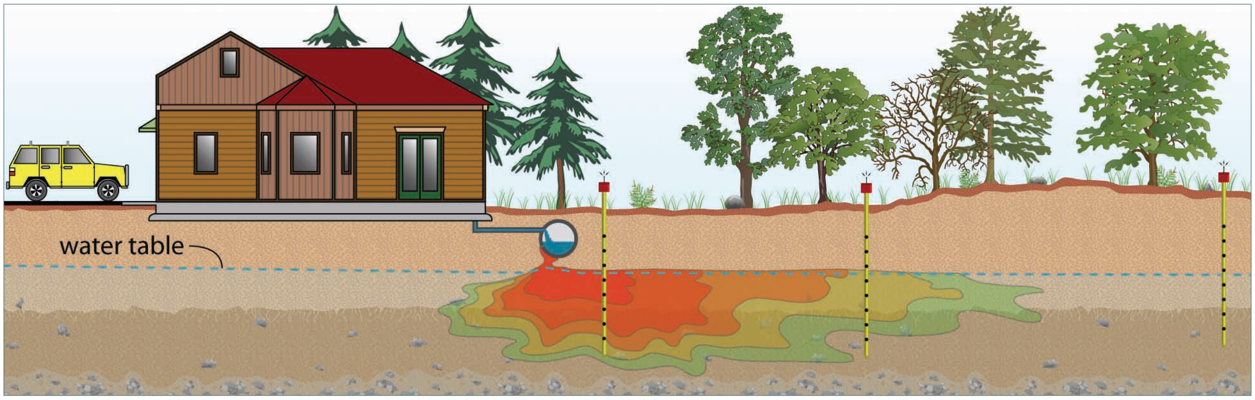

Figure 4.1 Illustration of a sensing system used to monitor aqueous contaminants in soil and groundwater. Sensors embedded in the soil and groundwater monitor a chemical plume spreading from a source, such as a septic tank. If concentrations become too high, the system generates an alert. *Illustration: J. Fisher, UC Merced.*

Demand for new septic systems will remain high as residential development expands to the exurbs. These new systems may either be installed individually for separate households (figure 4.1) or clustered to service entire subdivisions. Now, sensors can even be built into newly constructed systems, notifying homeowners of problems and offering self-regulating features triggered by excessive waste levels measured in the drainage field.

4.2 NON-POINT SOURCE RUNOFF

Pesticides and fertilizers are important components of conventional farming and lawn care, however they also can have a negative impact on fresh and marine water resources (Paul and Meyer 2001). Thus, it is imperative to balance farming and urban needs with those of watershed health. The current inability to track the location and quantity of pollution loads from regulated entities like municipalities prevents non-point source (NPS) pollution management through cap and trade programs.[2] Distributed sensing systems deployed at representative locations in combination with models of pollution distribution and dynamics can be used to generate robust estimates of loads and sources, allowing programs such as cap and trade to be implemented for water pollutants.

While NPS pollution is by its very nature distributed across large areas, surface and subsurface flows collect in a relatively few locations where they can be monitored. In addition, since quantification of total loads is needed for a cap and trade program, a measurement system must integrate fluxes continuously over time in order to measure total contaminate loads. Given these characteristics, a static sensing system is well suited to this task.

Two pollution-load pathways must be considered when monitoring runoff: (1) surface runoff carrying NPS pollution into ditches and drains, and (2) subsurface flows carrying NPS leachate through soils.

For surface runoff, drain outputs that empty directly into a stream can be fitted with static sensor nodes (figure 4.2). This system can include a flow-through electrical conductivity cell and a flow gauge to measure total aggregate contamination loads. For ditch-based systems, a similar sensing package can be installed or, where necessary, a javelin method, in which sensors are packaged in long hollow tubes and buried in the ground, can be employed. Currently available, electrical conductivity sensors are robust and will allow accurate sensing even after long durations of dry conditions both in the ditch and drain system.

To monitor groundwater, static sensing systems can be deployed in observation wells in areas hydraulically above and below each municipality participating in the cap and trade program. Each well can be fitted with a water level pressure transducer in addition to the electrical conductivity cell to determine groundwater conductivity and water level compared with in-stream flows.

If a more detailed understanding of location of sources and sinks is required within a municipality, a robotic sys-

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[2] Cap and trade programs use market-based mechanisms for reducing pollution by creating a variety of economic or market-oriented incentives and disincentives, such as tax credits, emissions fees, or tradeable emissions limitations. There are many types of incentive-based programs. Cap and trade programs work by setting a limit on the total amount of pollution that can be emitted (the so-called cap, which is lower than historical levels), allowing a certain amount of emissions by regulated entities, accurately tracking all pollution emitted, ensuring emissions are reduced to the capped level, and implementing a system for trading credits from reductions on an open market. An example of such a system is the EPA's Clean Air Market Programs.

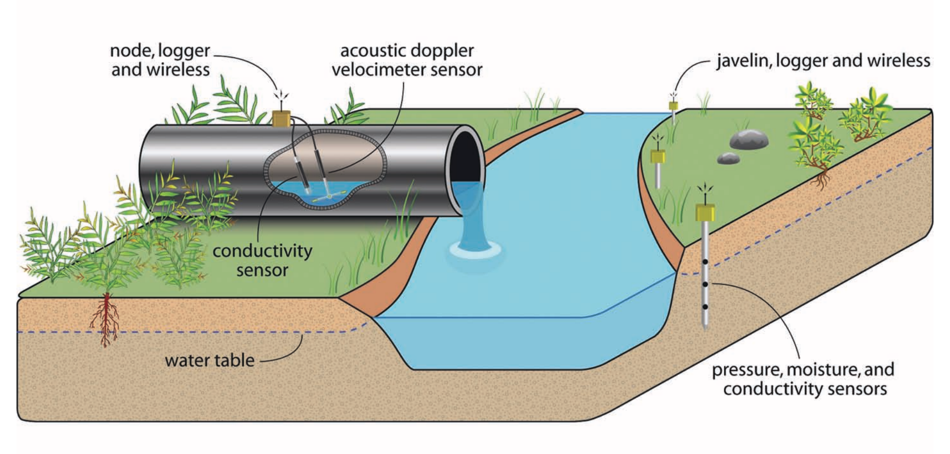

Figure 4.2 Illustration of a hypothetical non-point source runoff drain and javeline-based monitoring system.
Illustration: J. Fisher, UC Merced.

tem can be used to conduct a short term, spatially intensive survey of in-stream conductivity dynamics and, trigger actuated sample collection. For example, nitrate-ladened water could be collected and traced conclusively to a source via stable isotope analysis in a laboratory.

As the range of field-ready sensors expands, other static water quality sensors will help track specific ions such as nutrients, dissolved oxygen, chemical markers of human fecal contamination and organic compounds. This will allow for a cap and trade program that distinguishes specific water quality components rather than one that uses an aggregate measure of quality. Moreover, as power-saving technologies improve, the frequency of data collection and transmission can be increased, eventually leading to real-time, around-the-clock estimates.

4.3 BEACH WATER QUALITY

According to a recent report by the Natural Resources Defense Council, pollution-related closings and health advisories at U.S. beaches (such as that shown in figure 4.3) reached a record high in 2005 (NRDC 2006). Beach and near-shore water quality monitoring is a challenge because large areas must be monitored, water quality changes can happen quickly, and direct real-time *in situ* biological sensors are unavailable.

Current methods for monitoring recreational water quality use fecal indicator bacteria (FIB) as proxies for disease-causing organisms and require an incubation step of 18–96 hours. This incubation step makes protective actions such as preemptive beach closures impossible. Additionally, numerous studies have shown that current FIB levels do not always correlate with the actual level of pathogens. Much debate exists over the best pathogenic organisms to monitor, and significant research effort is now focused on direct, rapid detection of pathogens (ACT 2003b). Promising possibilities for rapid detection of FIB and pathogens are based on DNA and RNA amplification. However, such techniques are limited by cost, the need for specialized laboratory equipment, and the inability to distinguish between living and dead organisms. Rapid detection methods based on immuno-magnetic separation (IMS) followed by adenosine triphospate, or ATP, quantification are promising because they detect only live organisms. These methods are currently in the research stage.

Because of the challenges inherent in direct detection of pathogens, there is considerable interest in identifying

Figure 4.3 Beach Closure Sign, Siskiwit Beach, Bayfield County, WI. Beach closures due to pollution reached a record high in 2005, the last year for which data are reported (NRDC 2006).
Photo: G. Kleinheinz, UW-Oshkosh.

biomarkers for human fecal contamination, which are more feasible to detect with current sensor technology. For instance, recent research shows how changes in information theory indices (specifically Fisher Information Index and Shannon Entropy Index) calculated from frequent measurements of salinity and temperature (15 samples per hour measured by a single sensor package mounted on a pier piling) could indicate changes in water quality (Jeong et al. 2006). This discovery can contribute to the ongoing development of coastal ocean observatories consisting of static sensing systems (Edgington and Davis 2004, NOAA 2006), which may eventually make it possible to quickly indicate and localize changes in water quality at beaches. Such information could have a large public health benefit by signaling beach closures and warnings *before* people visit beaches.

Attaining complete coverage of large coastal areas using only static sensing systems is expensive and often impractical. Until coastal observatories are complete, event triggered handheld or robotic methods may be used to better characterize the formation and dissipation of harmful coastal events. For instance, by capitalizing on even weak correlations between poor water quality and other factors as well as on advances in rapid analysis techniques, a system that uses currently available data, such as precipitation, air and water temperature, could trigger humans or robots to collect water samples for laboratory analysis. These automated or semi-automated systems can help provide the data needed to decipher the mechanisms that control the pathogenic organisms that cause health problems. Armed with the understanding of how these events work will allow for more accurate predictions and forecasts.

4.4 COMBINED SEWER OVERFLOWS

Combined Sewer Overflows (CSOs) are a major source of river pollution in many older cities. During rain events, the sanitary sewage in the combined sewers mix with rain water flooding the sewer line interceptor, sometimes causing the mixed sanitary sewage and rain water to overflow untreated into streams (see figure 4.4). The biological oxygen demand (BOD) and pathogens from the untreated sanitary sewage pose great environmental and public health risks to streams and people. Embedded sensing systems have two potential management applications in the context of CSOs: (1) characterization of the distribution of the combined effluent for risk assessment and remediation purposes, and (2) incorporating triggered actuation to avoid, or minimize, overflows.

Figure 4.4 Sewage discharge into a receiving body. In older cities, wet weather events can overload combined sewage systems causing untreated sewage discharge into local waterways.
Photo: ©iStockphoto.com/JacobH.

CSO events are point sources of pollution that occur during wet weather events. As such, systems that can be deployed relatively quickly to sewer outfalls and receiving bodies would allow for multiple short deployments to characterize different outfall points. Both static and robotic sensing systems are available for such monitoring, with the robotic system providing high-spatial resolution information and the ability to acquire water samples at various points in the receiving body. A sensing system for monitoring the distribution of CSO effluent would need to identify the concentration and flow of the sanitary sewage effluent and potentially collect water samples during the event. As described above, field-ready sensors that can measure, for instance, electrical conductivity as an aggregate water quality measurement are currently available for *in situ* sensing systems, and, as other water quality sensors become field-ready, these systems are readily expandable. Ideal future sensor additions to the network are human pathogen sensors and chemical marker sensors. In the absence of more sophisticated sensors, manual or robotic physical sampling is needed to measure particular pollutants and pathogens.

A potential sensing system for tracking the distribution of effluent from a CSO involves (1) an electronic flow meter at the combined sewer overflow outlet for gauging the effluent, (2) an electrical conductivity sensor at the outlet to determine the TDS exiting the outlet, and (3) an array of conductivity sensors in both the channel and bank sediments. If needed, robotic systems can be deployed to measure conductivity and flow in profiles across the receiving body to provide information about finer scale mixing dynamics. Moreover, static sensors can trigger such a system to collect water samples at appropriate points and times. By tracking the location and height of the spikes in conductivity, municipalities could characterize and model the direction and dispersion of the contamination plume allowing them to assess compliance with local and federal water quality regulations.

Another promising application of wireless sensing systems in the context of combined sewers is associated with creating feedback-control systems for avoiding overflows. Such systems will require significant flood storage capacity in the form of underground cisterns or storm water retention ponds. Prototypes of such augmented systems are currently undergoing testing. For example, a pilot system, deployed in December 2004, has been collecting (1) near real-time hydraulic and water quality data and (2) water level data for the combined sewer system for the Boston Water and Sewer Commission (Stoianov et al. 2006). In this case, the goals of monitoring the combined sewer system include detection of failures (through acoustic or vibrational monitoring using accelerometers or hydrophones flanking suspected leaks) and the contribution of data to a real-time control system, which is a cost-effective alternative to CSO management when compared to construction projects. Another CSO sensing system being piloted in South Bend, IN employs a network of sensor nodes to track flows in a combined sewer system and to actuate valves to shunt flows to retention basins when the threat of a CSO event is high (Ruggaber et al. in press).

Wet weather discharges are a significant cause of water quality problems nationwide. Methods that can help assess the consequences of discharges and technologies that can prevent them are both needed to advance the management of urban water systems.

5. RECOMMENDATIONS FOR RESEARCH

Embedded networked systems are an emerging technology. Substantial success in research and development activities has given rise to the systems described in this report—systems that have been successfully deployed but in a relatively small set of real-world applications. The time is ripe to expand the range of applications where embedded sensing systems are used to help mature the technology and further expand the uses. Next steps in the maturation of this technology should involve applying and testing systems in situations where they can yield important results. Only through branching out in this way will embedded sensing systems help to realize the full vision set out in the scenarios presented in this report.

The following summary of recommendations is intended to assist organizations and agencies that stand to benefit from novel uses of embedded sensing systems. These recommendations can be used to plan for investments in the continued development of these systems for widespread use. By taking these key actions, the field of embedded networked sensing will continue its evolution and realize the potential for more effective management of our critical water resources.

5.1 SENSORS AND ACTUATORS

Small, rugged, field-ready sensors suitable to deploy for long periods in harsh environments are not currently available for the full range of environmental sensing situations envisioned. This is especially true of biological and chemical sensors. Two investments should be made to help fill the gap: (1) long-term research and development for sensors where new or improved detection methods are needed and (2) short-term market incentives targeted at moving already well-developed sensing technology from research prototypes to commercially available products.

Long-term research is needed to develop detection methods for:

- carbonaceous compounds
- heavy metals
- large molecular mass molecules such as dissolved organic compounds and dissolved organic nitrogen compounds
- pathogenic organisms
- biologically-active compounds such as toxins
- biomarkers
- lab-on-a-chip sensors

In addition, research on methods to minimize sensor maintenance in the field will expand the ability to deploy autonomous systems and will result in higher quality data.

In some cases, sensing technologies have passed through the research and development stage and exist as prototypes, but they remain basically unavailable for large-scale use. In such cases, investments are needed to bring these technologies to market in forms suitable for environmental sensing. This is especially true for nitrate sensors, where the potential to realize substantial returns on investments is large.

If specifications for certain sensors (e.g., precision, service life, service conditions) were explicitly determined for applications that are expected to be widely used and supported, it would give companies the information they need to develop specific products to meet the expected demand.

5.2 DEPLOYMENT PLATFORMS

Static, robotic, and handheld sensing systems have been deployed in a handful of environmental science and monitoring related situations. Investments are needed in a larger range of pilot studies to determine specific requirements and solutions for particular investigations, whether they be for septic systems or sewage discharges. At this time, deployments generally still require considerable attention by engineers and scientists to customize systems to specific environments and to specific measurement tasks. Providing incentives for companies to package sensing systems for use in particular tasks is an important step in making this technology accessible to the intended user base—environmental scientists and resource managers—and not just to computer scientists and electrical engineers. Pilot studies will be critical to providing the testing and specialization required for these systems to mature to a point where they are viable tools for environmental monitoring. When that has occurred, there will be incentive for commercial production of the systems that are robust, well documented, and broadly useable.

5.3 THE DATA LIFE CYCLE

Similar to sensing platforms, tools to manage the full data life cycle in a networked sensing system already exist and have been field-tested in limited circumstances. Again, pilot deployments should be encouraged to test and refine data management tasks for specific applications. This includes sampling design, operation of the systems, and data analysis. Continued research and testing of tools to improve system robustness and ensure high-quality data is needed. Environmental monitoring efforts also stand to benefit from additional focus on the integration of sensing systems with external data sources and third-party applications, especially map-based visualization with tools for both rigorous GIS techniques and more public friendly web applications.

5.4 OTHER RECOMMENDATIONS

There are a vast number of possibilities for using embedded sensing systems for water quality management. However, resource managers and system designers, jointly, need to make decisions about which opportunities promise the largest return. Furthermore, it is important to ensure that environmental professionals in all sectors are prepared to use these new complex systems. To this end, investment in training is critical. Training at multiple levels is necessary to ensure that a ready workforce exists that is prepared use these new sensing technologies. Support for undergraduate and graduate level multidisciplinary programs is crucial to expose students to the variety of disciplines that come together in these systems: computer science, electrical engineering, environmental engineering, and the biological sciences. In addition, professional development for the current environmental work force is needed and can be achieved through direct training and facilitating partnerships between vendors, environmental science and engineering firms, and academia.

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RICHARD AMBROSE is a Professor in the Department of Environmental Health Sciences and Director of the Environmental Science and Engineering Program at the University of California, Los Angeles. Dr. Ambrose's research focuses on ways to protect and maintain the ecology of coastal areas; much of his work is conducted at the interface between environmental biology and resource management policy. His current research focuses on (1) restoration of degraded habitats, especially for coastal marine environments, and (2) assessment of the health of coastal ecosystems. Dr. Ambrose and his students have studied the cumulative effects of impacts to riparian systems and the success of wetland/riparian mitigation required under Sections 404 and 401 of the Clean Water Act. His research on ecosystem health includes a program to monitor rocky intertidal habitats (with a particular focus on being able to detect short-term effects, such as those caused by oil spills, as well as long-term effects of global climate change) using a network of sites throughout southern California. Dr. Ambrose's research in coastal watersheds focuses on establishing a link between land use and aquatic community health. All of these projects provide information on the status of important coastal ecological communities, including the nature and extent of anthropogenic impacts on them, which serves as the foundation for their management and protection.

DAVID A. CARON is a Professor in the Marine Environmental Biology section of the Department of Biological Sciences at the University of Southern California (USC). He has a B.S. in Microbiology and a M.S. in Oceanography from the University of Rhode Island, and a Ph.D. in Biological Oceanography conferred jointly by the Massachusetts Institute of Technology and Woods Hole Oceanographic Institution. His research involves marine and freshwater microbial ecology, with emphasis on the food web relationships among unicellular microorganisms (algae and protozoa). Ongoing research programs in his lab include field and laboratory studies of harmful bloom-forming species of microalgae, and investigations of the biodiversity and physiology of temperate, tropical and polar microbial communities. He is a recipient of the Mary Sears Chair for Excellence in Biological Oceanography (from Woods Hole Oceanographic Institution), the Seymour Hutner Award (from the Society of Protozoologists), and a recent president of the International Society of Protistologists. He has served as Section Head within the Marine Environmental Biology section and as Chairperson for the Department of Biological Sciences at USC.

DEBORAH ESTRIN is a Professor of Computer Science at the University of California, Los Angeles (UCLA), holds the Jon Postel Chair in Computer Networks, and is Founding Director of the National Science Foundation-funded Center for Embedded Networked Sensing (CENS). Estrin received her Ph.D. in Computer Science from the Massachusetts Institute of Technology in 1985, and her B.S. from the University of California, Berkeley in 1980. Before joining UCLA, she was a member of the University of Southern California Computer Science Department. In 1987, Professor Estrin received the National Science Foundation, Presidential Young Investigator Award for her research in network interconnection and security. During the subsequent 10 years, much of her research focused on the design of network and routing protocols for very large, global, networks, such as: scalable multicast routing and transport protocols, self-configuring protocol mechanisms for scalability and robustness, and tools and methods for designing and studying large scale networks. Since the late 90's, Professor Estrin has been collaborating with her colleagues and students to develop protocols and system architectures needed to realize rapidly-deployable and robustly-operating networks of physically-embedded devices. She is particularly interested in the application of spatially and temporally dense embedded sensors to environmental monitoring. Most recently this work includes participatory-sensing systems, based on automated, programmable, and adaptive collection of environmental, physiological, and social parameters at the personal and community level. These systems will leverage the installed base of image and acoustic sensors that we all carry around in our pockets or on our belts—cell phones.

JASON C. FISHER is a Postdoctoral Scholar in the School of Engineering at the University of California, Merced. He received his B.S. in Environmental Resources Engineering in 1998 and a M.S. in Environmental Systems in 2000 from the Humboldt State University. In addition, he received M.S. (2003) and Ph.D. (2005) degrees from the Civil Engineering program at the University of California, Los Angeles. His current research interests include the numerical modeling of flow and contaminant transport in groundwater systems, the interaction between groundwater and surface water, optimization techniques applied to water resources management models, data processing and visualization, and graphic design. Dr. Fisher is currently participating in a study of the nitrate and salt distributions within the San Joaquin River Basin, CA.

ROBERT GILBERT is a doctoral candidate in the department of Environmental Health Science at the University of California, Los Angeles. Prior to his doctoral work, Mr. Gilbert received a B.S. in Resource and Ecology Management from the School of Natural Resources and Environment at the University of Michigan, Ann Arbor. Mr. Gilbert is interested in urban stream characterization specifically as it relates to algal dynamics. He is combining a robotic sensing system with static sensor arrays and an algal productivity bioassay in order to quantify in stream physical, chemical, and algal conditions in a way that enables comparability both within and between stream reaches. Being able to determine and accurately relate the conditions that lead to the observed algal biomass is critical to characterizing the relationships between urban stream quality and algal dynamics.

MARK H. HANSEN is an Associate Professor and the Vice Chair for Graduate Studies in the Department of Statistics at the University of California, Los Angeles. Previously, he served as a Member of the Technical Staff in the Statistics and Data Mining Research Department at Bell Laboratories, Lucent Technologies. His current work examines "data flow" (a pipeline leading from collection methodologies, through analysis and modeling, to policy formulation and decision making) through the context of specific institutions and locations throughout the Los Angeles area. Dr. Hansen is a Co-PI for the Center for Embedded Networked Sensing. His work has been recognized with a 2005 Media Arts Fellowship (joint with media artist Ben Rubin); Hansen and Rubin are also recipients of the Ars Electronica 2004 Golden Nica for Interactive Art. Dr. Hansen received a M.S. and Ph.D. in Statistics from the University of California, Berkeley and a B.S. in Applied Mathematics from the University of California, Davis.

THOMAS C. HARMON is a Professor in the School of Engineering and Founding Faculty member at the University of California, Merced. He directs contaminant observation and management application area for the Center for Embedded Networked Sensing, and is co-chair of the sensor networks subcommittee within the national WATERS Network proposal development effort. Professor Harmon received a B.S. in Civil Engineering from the Johns Hopkins University in 1985, and M.S. and Ph.D. degrees from the Environmental Engineering program at Stanford University in 1986 and 1992.

JENNIFER JAY is an assistant professor in the University of California, Los Angeles Department of Civil and Environmental Engineering. Professor Jay's research integrates field and laboratory approaches to better understand the geochemical and microbial processes that govern the fate of contaminants in the environment. Specific interests include the geochemical and microbial methylation of mercury by sulfate-reducing bacteria (the end-product of this reaction, methylmercury, is a potent neurotoxin with a very strong tendency to bioaccumulate), the mobilization of arsenic in groundwater, and the persistence of fecal indicator bacteria and pathogens in beach sediment. Understanding the cycling of contaminants in aquatic systems allows us to better assess and minimize hazards associated with environmental contamination, and to more accurately predict effects of environmental perturbations. Professor Jay received the Presidential Early Career Award in Science and Engineering (PECASE) in 2004, the same year she received an NSF Early Career Development

(CAREER) Award. In 1999, she was selected as a Martin Family Society Fellow for Sustainability and in 1991 she won a Parsons Fellowship. Dr. Jay received her B.S., M.S. and Ph.D. from the Massachusetts Institute of Technology.

WILLIAM J. KAISER received a Ph.D. in Solid State Physics from Wayne State University in 1984. From 1977 through 1986, as a member of Ford Motor Co. Research Staff, his development of automotive sensor and embedded system technology resulted in large volume commercial sensor production. At Ford, he also developed the first spectroscopies based on scanning tunneling microscopy. From 1986 through 1994, at the Jet Propulsion Laboratory, he initiated the NASA Microinstrument program for distributed sensing. In 1994, Professor Kaiser joined the faculty of the the University of California, Los Angeles Electrical Engineering Department at which time, along with Professor Greg Pottie, he initiated the first wireless networked microsensor programs with a vision of linking the Internet to the physical world through distributed monitoring. This continued research includes the topics of actuated sensor networks for environmental monitoring, self-organized networked embedded systems, low power integrated circuits and systems for wireless networked sensing, and biomedical embedded computing platforms. Professor Kaiser served as Electrical Engineering Department Chairman from 1996 through 2000. Dr. Kaiser has over 160 publications, 120 invited presentations, and 23 patents. He has received the Allied Signal Faculty Research Award, the Peter Mark Award of the American Vacuum Society, the NASA Medal for Exceptional Scientific Achievement, the Arch T. Colwell Best Paper Award of the Society of Automotive Engineers, two R&D 100 Awards, and the Brian P. Copenhaver Award for Innovation in Teaching with Technology. He is co-founder of Sensoria Corporation.

GAURAV S. SUKHATME is an Associate Professor of Computer Science (joint appointment in Electrical Engineering) at the University of Southern California (USC). He received his undergraduate education at IIT Bombay in Computer Science and Engineering, and M.S. and Ph.D. degrees in Computer Science from USC. He is the co-director of the USC Robotics Research Laboratory and the director of the USC Robotic Embedded Systems Laboratory, which he founded in 2000. His research interests are in multi-robot systems and sensor/actuator networks. He has published more than 120 papers in these and related areas. Professor Sukhatme has served as PI on numerous National Science Foundation (NSF), Defense Advanced Research Projects Agency and National Aeronautics and Space Administration grants. He is a member of the American Association for Artificial Intelligence, the Institute of Electrical and Electronics Engineers (IEEE) and the Association for Computing Machinery, and is a recipient of the NSF CAREER award. He has served on many conference program committees, recently co-chairing the program committee of the first Robotics: Science and Systems conference. He is the Associate Editor of Autonomous Robots, and an Associate Editor of the IEEE Transactions on Robotics and Automation, both leading journals in robotics. He is on the editorial board of a leading magazine in ubiquitous computing, IEEE Pervasive Computing.

YU-CHONG TAI is a Professor of Electrical Engineering, Mechanical Engineering and Bioengineering at the California Institute of Technology (Caltech). He is also currently the department Chair of Electrical Engineering. Since 1983, his main research interest has been micro-electro-mechanical systems (MEMS), sensors and actuators. Professor Tai developed the first electrically-spun polysilicon micromotor while at UC Berkeley and he joined Caltech in 1989 after PhD education. At Caltech, he built the Caltech Micromachining Lab, which is a 100% MEMS facility with 8,000 square feet of laboratory (including 3,000 square feet of class-100 clean room). His research group consistently numbers more than 20 researchers working on various MEMS projects such as integrated microfluidics, bio MEMS, smart skins, labs on-a-chip, and MEMS neural implants. He has published more than 250 technical articles in the field of MEMS. He is the recipient of the IBM Fellowship, Ross Tucker Award, Best Thesis Award (at Berkeley), Presidential Young Investigator Award, Packard Award, 2002 ALA Achievement Award. He was the General co-Chairman of the 2002 Institute of Electrical and Electronics Engineers (IEEE) MEMS Conference. He was a Section Editor of the Sensors and Actuator and a Subject Editor of the IEEE/American Society of Mechanical Engineers *Journal of MEMS*. He is a fellow of IEEE and a Fellow of the Institute of Physics.

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