Continuous Plume Monitoring Using Wireless Sensors: Proof of Concept in Intermediate Scale Tank

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Abstract: The current practice for monitoring of subsurface plumes involves the collection of water samples from sparsely distributed monitoring wells and laboratory analysis to determine chemical concentrations. In most field situations, cost and time constraints limit the number of samples that could be collected and analyzed for continuous monitoring of large, transient plumes. With the development of wireless sensor networks (WSNs), that allow sensors to be incorporated into a distributed wireless communication and processing system, the potential exists to develop new, efficient, economical, large-scale subsurface data collection and monitoring methods. This paper presents a proof-of-concept study conducted in a two-dimensional synthetic aquifer constructed in an intermediate scale test tank to demonstrate the feasibility of using WSN for subsurface plume monitoring. The tank was packed to represent a heterogeneous aquifer, and a sodium bromide tracer was used to create a plume. A set of ten wireless sensor nodes (motes) equipped with conductivity probes to measure electrical conductivity formed the network. Software for automated data acquisition was developed and tested. Results of two experiments conducted using this test system are presented. The lessons learned from the first experiment were used to make modifications to the way the sensors were placed, how they were calibrated and how the sensors were interfaced with the data acquisition system. The findings are used to identify future research directions and issues that need to be addressed before field implementations of a WSN based data collection system for plume monitoring.

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Introduction and Background

Maintaining a reliable supply of potable water with acceptable quality is of primary interest to water managers and planners. Groundwater monitoring is an important component in the design of strategies for site remediation and subsequent performance assessment. Data gathered during site characterization is used to build and calibrate groundwater flow and transport models to predict plume behavior in the subsurface.

Subsurface characterization presents numerous challenges. Heterogeneity in the subsurface resulting from the spatial variability of soil properties cannot be fully characterized using only a limited number of bore holes. Pumping tests are useful only to determine effective parameters for subzones of the aquifer. It is also not always possible to optimally locate the monitoring wells to sample the plume to obtain data for transport model calibration. The high cost of monitoring well installations and laboratory analysis of samples places limits on the number of samples that can be collected and analyzed to fully define the spatial and temporal behavior of the plume. With traditional sampling methods, the data collection is limited by time and cost constraints, and often fails to capture the actual plume (Puls and Paul 1997). These limitations, in turn, impair the ability to build reliable predictive models for remediation strategy decisions.

New sampling protocols combine the use of different types of sensors with traditional sampling techniques. The development of more sophisticated sensors makes it possible to use them as the sole data gathering method. Sensing permits in situ monitoring and real-time data collection. Environmental sensors are usually grouped into three different categories, based on the type of characteristic they "sense": physical, chemical, and biological (Goldman et al. 2007). While ion selective sensors and chemiresistors (Ho et al. 2001; Ho and Hughes 2002) are very sophisticated and permit a direct measurement of the chemical of interest in the subsurface, they are not very durable and require much maintenance (Ramanathan et al. 2006). Thus, they are not suitable for long-term field monitoring applications. An alternative to these chemical sensors are the electrical conductivity sensors, which detect changes in salinity or resistivity in the medium in which they are placed. These alternative sensors have been used widely by different research groups to detect subsurface contamination (Kaya and Fang 1997; Kechavarzi and Soga 2002). The sensors can be calibrated by measuring the electrical conductivity value

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for different salt solution concentrations. The resulting calibration curve is used to convert electrical conductivity to contaminant concentration in the field or laboratory. Conductivity sensors are usually less expensive, more robust, and require minimum maintenance.

Sensors enable continuous monitoring, as opposed to "single-shot" testing as in conventional sampling. Laboratory and personnel costs are reduced as well when sensors are used. So far, sensors have been used primarily in combination with handheld meters or with data loggers connected to a computer to view the data. Handheld meters are cumbersome in that a physical presence on the site is required for every measurement taken. The data loggers make use of large amounts of wiring from the sensors to the data logger and computer, which can present a hazard in the field.

Wireless sensor networks (WSN), an emerging technology, can be used to overcome many of the problems associated with traditional schemes. A WSN is composed of a set of nodes, often referred to as motes, each equipped with a sensor, a processor, and a wireless transmitter/receiver. The nodes are thus capable of sensing a phenomenon, processing the information, and wirelessly exchanging the information among each other and with a computer (Akyildiz et al. 2002). Recent applications of WSNs include traffic control, military applications, and environmental monitoring. The WSNs make it possible to monitor physical phenomena at a far higher granularity in space and time than has been possible in the past.

For groundwater monitoring applications, the use of wireless sensors is more challenging since wireless boards cannot be placed directly in the subsurface due to radio communication problems and environment hostility. A solution to these problems is the use of regular sensors placed inside a monitoring well and connected to a mote placed on top of the well. Motes then communicate the data wirelessly among each other and with a computer. The mote, which is a minicomputer that can be programmed independently from the rest of the system, excites the sensors for data collection, and acts as an intermediary between the sensor and the data-processing computer. With such a system, data can be gathered and transmitted quickly and without any manual intervention.

With the large-scale deployments of wireless sensors, more data can be gathered at a site, improving the spatial as well as the temporal data collection, since the sampling frequency can be greatly increased by using motes. Moreover, the data sampling process, e.g., sampling frequency and accuracy, can also be adaptively reconfigured. Local processing in motes can be used to identify the onset of events, which triggers changes in sampling and network activity. Motes can make decisions based on the user-programmed tasks and the outputs from the sensors before communicating with the server.

Wireless sensing technology appears to be an attractive tool for groundwater contamination problem applications to enhance the quality of sampling systems and groundwater modeling tools. The idea is to employ the motes and sensors for a smarter data collection and use these data for automated model calibration. Before such an innovative system can be implemented in the field, laboratory experiments are required to identify and overcome certain technological challenges. Examples of challenges include sensor calibration, installation and distribution, automation of real-time data collection, and automated calibration of groundwater models. To address these challenges and develop techniques suitable for the field, an intermediate scale laboratory proof of concept study was conducted using a simple two-dimensional test system. This paper starts by presenting the equipment used for the experiments and describing the sensor calibration method employed. Then, two sets of experiments are described and their outcomes presented. Finally, conclusions, recommendations for future work and field applications are expressed.

Experimental Methods and Materials

Materials and Equipment

Motes

A central component in a wireless sensing project is the mote: a wireless sensing board that transmits data via radio communication. For this project, ten motes were purchased from Crossbow Technology, Inc., the vendor for wireless modules developed by the University of California at Berkeley. The motes chosen for this study are the TPR2420CA TelosB motes, herein referred to as the TelosB. These research platforms provide a low power IEEE 802.15.4 compliant wireless sensor module with a built-in antenna and programming and data collection capability via universal serial bus (USB). Low power consumption allows for long battery life. The TelosB, released in 2004, was chosen for its compact design and its integration of programming, computation, communication, and sensing onto a single device (Polastre et al. 2005). TelosB is very appropriate for field applications and long-term deployment.

Sensors

In this work, the contaminant plume was created using a bromide tracer, making it possible to use electrical conductivity sensors to monitor the plume. Electrical conductivity (EC) sensors were used to measure differences in salinity or resistivity between clean water and a contaminant plume. The sensors needed to be accurate, but also robust for subsurface conditions. Another factor of concern was the connectivity between the sensors and the motes. Most commercially available sensors require an external circuit as an interface before connection to the motes to read and output data. The additional interface between the sensor and the mote increases the overall cost and might complicate the software development for mote to sensor communication. Therefore, a sensor which integrates a serial digital output would be ideal and most effective for use with motes.

The sensor of choice for this proof of concept study was the ECH_2O-TE purchased from Decagon Devices, Inc. Decagon Devices manufactures very robust moisture sensors that are primarily used in the agricultural and botanical research fields. Decagon recently developed a probe that measures soil moisture content, electrical conductivity, and temperature at the same time. The ECH_2O-TE probe adjusts conductivity measurements with temperature, improving the overall conductivity reading accuracy.

The ECH_2O-TE sensors are usually employed in conjunction with a data logger. However, its simple input-output operation and low power requirements make it ideal for use with the TelosB. The ECH_2O dielectric soil moisture sensors (which do not include electrical conductivity measurements) have been used in previous research projects in conjunction with similar wireless platforms that are used in the current project (Cardell-Oliver et al. 2005; Ramanathan et al. 2006). These projects were geared toward water content measurements in the topsoil and the unsaturated zone, respectively.

Table 1. Sand Properties

Sand sieve size	#16	#30	#50	#70	#110
Hydraulic conductivity[a] (cm/day)	37,200	12,960	3,190	1,160	362
Porosity[b]	0.407	0.433	0.426	0.418	0.334
Longitudinal dispersivity[c] (cm)	0.112	0.058	0.062	0.227	N/A

Note: N/A=not available.

[a]Barth et al. 2001.

[b]Limsuwat and Sakaki 2007 (unpublished). Mean values for tightly packed column.

[c]Fernandez-Garcia et al. 2004.

One of the main challenges of the proof of concept setup was the conversion of sensor outputs from the motes to obtain readings with the desired units. To take the readings, an excitation voltage of 3–15 V needs to be applied to the sensor; the output data are delivered as a serial digital output. For the initial sensor and mote communication trials a sensor was modified to support the mote's 16-bit connector and the communication was successfully established. Each mote contains only one external universal asynchronous receiver/transmitter (UART) interface, which means only one sensor can be connected to each mote. The UART interface translates data between the mote (parallel output) and the sensor (serial output). However, with the relatively small scale of the physical test bed in the laboratory, it was more practical to allow for more sensors to be connected to each mote. To this end, a breakout box was built for each mote to support up to four sensors each. Indicator lights at each radio plug indicated which sensor was active.

Test Bed

The laboratory sands used in these proof-of-concept experiments were purchased from Unimin Corporation in Idaho. These test sands have been well characterized and used extensively in our past research (Barth et al. 2001; Moreno-Barbero and Illangasekare 2006). Characteristics of these sands are given in Table 1.

All of the experiments were conducted in a Plexiglas tank with dimensions: 244 cm long × 44 cm deep × 8 cm wide. The water inlet and outlet were drilled into the aluminum end pieces, approximately 14.5 cm from the bottom of the tank. Two constant head devices were attached to the inlet and outlet to ensure a steady flow through the tank. The tank was supplied with filtered and deaired water.

Experimental Setup and Procedures

Sensor Calibration

A sodium bromide (NaBr) solution was used as a tracer in the experiments. Therefore the sensors were calibrated to this tracer. The sensors were calibrated separately with eight different sodium bromide solutions. The concentrations used were 1,000, 800, 500, 200, 100, 20, 5, and 0 mg/L of NaBr in a solution of filtered tap water (identical to the water flowing through the tank). Beakers with these solutions were prepared and each sensor was submersed into the solutions one at a time with deionized water rinses between each insertion into a different solution. For each sensor, the electrical conductivity reading taken with a mote was recorded. For the first readings, the mote outputs were tested against the reading given by a Campbell data logger (CR10X) to ensure the units were correct and the motes communicated the correct data. The standard concentration versus the sensor reading was plotted and a straight line fitted through the points. The measurement points followed a linear regression, which is typical for very low salt concentrations, and the results are consistent with published data for natural waters (Hem 1985). Fig. 1 shows the calibration plot for Sensor 1 in solution. The graphs for Sensors 2–10 are very similar.

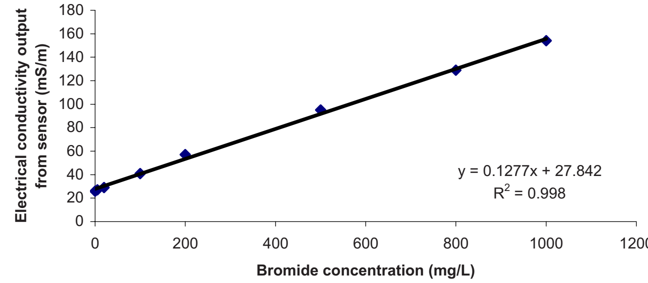

Fig. 1. Calibration curve for Sensor 1 in solution

Fig. 1 provides the electrical conductivity to concentration relationship in solution only, which is equivalent to pore-water values in a sandy medium. However, since the sensors were placed directly in the sand for the first experiment, the values given by the sensors represented the bulk electrical conductivity measurements.

The Decagon manual for the ECH_2O-TE probe suggests a formula for obtaining pore-water conductivity from bulk measurements and vice versa. This formula is taken from the work presented by Hilhorst (2000) which is based on the linear relationship between the soil bulk dielectric permittivity and the bulk soil conductivity. This relationship takes into account the raw water content (i.e., uncalibrated, as measured by the probe) and the soil temperature, both measured by the ECH_2O-TE probe

$$\sigma_p = \frac{\varepsilon_p \sigma_b}{\varepsilon_b - \varepsilon_{\sigma b=0}} \quad (1)$$

where σ_p=pore water EC (mS/m); σ_b=bulk EC (mS/m); ε_p=real portion of dielectric permittivity of soil pore water; $\varepsilon_p = 80.3 - 0.37^*(T_{\text{soil}} - 20)$; T_{soil}=soil temperature (°C) measured by the probe; ε_b=real portion of the dielectric permittivity of the bulk soil; $\varepsilon_b = (7.64^* 10^{-8*}\ \text{Raw}^3) - (8.85^* 10^{-5*}\ \text{Raw}^2) + (4.85^* 10^{-2*}\ \text{Raw} - 10)$; Raw=raw water content measured by the probe; and $\varepsilon_{\sigma b=0}$=4.1; offset representing the dielectric permittivity of the dry soil.

The manual states that this formula gives results with a ±20% accuracy, which is poor and can induce significant errors in the calibration curve. However, at very low sodium bromide concentrations, between 0 and 200 mg/L, this relationship estimated pore EC values close to measured ones. Several sensor tests were conducted by measuring both the conductivity in sand saturated with the solution and in the solution only.

For the first set of experiments, in which the sensors were directly placed in the sand, sensor calibrations in sodium bromide solutions were performed. The bulk conductivity values taken by the sensors during the experiments were converted to pore EC values with the Hilhorst (2000) formula, and finally converted to tracer concentration by using the initial calibration functions.

The above calibration method description is referred to as an "ex situ calibration" since the sensors are not placed inside the medium in which they are taking measurements. Initial experi-

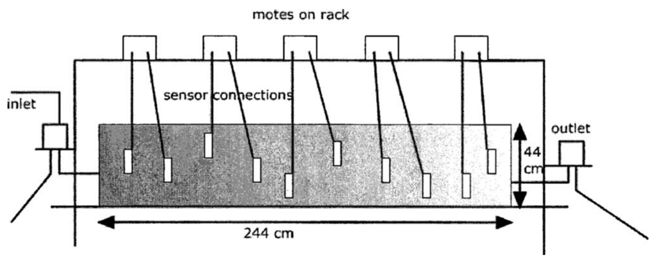

Fig. 2. Test bed set up diagram (not to scale)

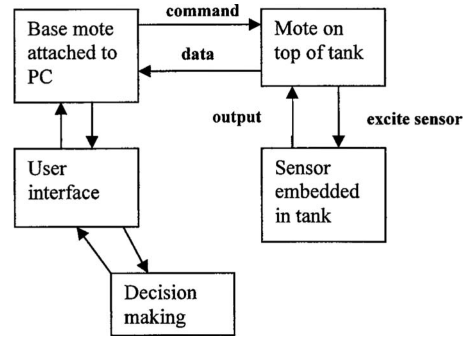

Fig. 3. Schematic of the wireless sensing communication system

mental results, however, showed that readings taken by the sensors outside of the tank and once packed in the tank are quite different. It is hypothesized that these differences are due to different conditions like salt content of the sands, pressure, and temperature, which greatly affect conductivity measurements. As a result, a different calibration method was devised for the second set of experiments. Namely, the "in situ" calibration procedure consists in taking manual aqueous samples from the same location where the sensors were placed in the flow system. Aqueous samples were analyzed with an ion chromatograph (IC) to measure the concentration of bromide ions. Finally the manual results were compared to the sensing data. If a good agreement occurred, the data could be used for calibration of the sensors. This method ensures a more reliable data analysis since the sensors are calibrated in the medium in which they take the measurements. The in situ calibration method is described in more details in the results section.

Test Bed Setup

For each experiment, the tank was filled with the appropriate test sands and the ten sensors were placed in the sand while packing, according to the sand distribution created with an initial groundwater flow model. The tank was wet packed; as the water level in the tank was slowly raised (a few centimeters at a time), the sand layers were filled in with use of a paper cup and a PVC pipe topped with a plastic cone.

The first 10 cm at the inlet of the tank and the last 10 cm before the outlet were filled with clean coarse gravel over the entire depth of the tank. The gravel allowed the water flow to be uniform along the depth of the tank, which simulated a plug flow through the sand. In addition, in between the gravel and the actual sand layers, a screen made out of perforated aluminum plates covered with insulation material and fine aluminum mesh prevented sand from moving to the inlet/outlet ports and subsequently clogging them. Two manometers were placed 1 cm from the bottom of the tank into the gravel portion to accurately monitor the head at the inlet and outlet of the tank. The manometers were used as indicators to adjust the constant head devices.

The sensors were placed within the tank and wired to the breakout boxes specifically built for a better sensor-to-mote interface. The motes were enclosed in a small transparent plastic box to prevent water and sand from damaging them, and double taped to the breakout boxes which were attached to a 152 cm tall rack above the tank (see Fig. 2). The five motes used in this experiment were placed about 30 cm apart, and each had one, two, or three sensors attached to them (for a total of 10 sensors placed in the tank). The motes were powered via USB connections to a regular power supply. The base mote, which transmits commands wirelessly to the other motes and receives all the data to be stored, was connected to the computer at all times. The base mote was the bridge between the physical test bed and the data acquisition system on the computer.

Wireless Data Collection and Management

The individual motes were programmed in advance to respond to a command from the base mote. The command triggered the mote to excite the sensor attached to it by applying a voltage. The sensor responded by instantly outputting a reading that wirelessly transmitted back to the base mote. The frequency of measurements was controlled by the user through a custom-designed interface. The user typed in commands (such as time interval of sampling and sensors to be excited), which the base mote wirelessly communicated to the tank motes. This program provided a display for incoming data; one tab for each mote provided information about the time a reading was taken with which sensor, and a column for each data (temperature, water content, and conductivity). Fig. 3 provides a schematic of the wireless sensing communication system.

Results and Discussion

Two sets of experiments were performed with different sand packing configurations.

Experiment 1

The purpose of the first experiment was to test and evaluate the wireless communication and response of the sensors and the motes to a controlled "spill" in a physical test bed. A qualitative analysis of the sensor data was performed and the calibration method was evaluated.

The packing configuration consisted of rectangular sand blocks, each containing one sand type with a height close to the sensor length (12 cm long and 3 cm wide). Five different sand types were used to create an artificial heterogeneity in the tank. The well-characterized sands used to create the synthetic aquifer were Tyler Mesh size #16, #30, #50, #70, and #110. The properties of these sands are given in Table 1. To evaluate different packing configurations of these sand blocks in the tank, a groundwater flow model was developed using MODFLOW-2000 contained inside the GMS 6.0 interface.

A 200 mg/L sodium bromide (NaBr) solution was injected into the #16 layer in the tank, about 10 cm upstream of the first sensor. The injection rate was set to 14 mL/min (20 L/day) which was slightly lower than the total water flow through the tank (24 L/day, as measured from the outlet) in order not to significantly

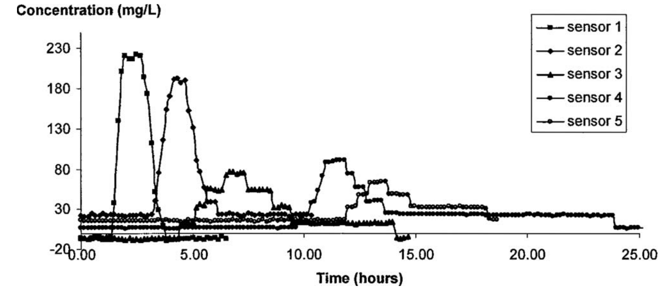

Fig. 4. Combined breakthrough curves for Sensors 1–5 with calibrated values

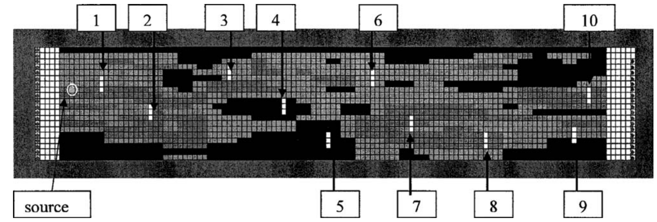

Fig. 5. Final sand distribution model after tank packing and sensor placement

change the natural flow field. The total injection volume was 560 mL, over a period of 1 h. The flow in the tank was controlled with two constant head devices: one at the inlet, setting the hydraulic head at about 40 cm (top of the tank), and one at the outlet, placed about 3 cm below the top of the tank.

Tracer concentration data were collected from every sensor with the wireless sensing system continuously every 10 min until the tracer was completely flushed out of the tank. At this point the sensor readings were back to base readings, signifying that no more tracer was present in the tank. As the tracer solution was transported with the water flow, the sensors detected the change in electrical conductivity. The first five sensors in the tank monitored the tracer, but the other five sensors did not record any changes in the conductivity. The same tracer test was repeated twice to check for consistency of the wireless data gathering system, which was validated.

Breakthrough curves of electrical conductivity were obtained for each sensor. Fig. 4 shows the calibrated breakthrough curves for the sensors. The graphs clearly show the advective-dispersive flow pattern of the tracer in the tank. Indeed, the first two curves show a very narrow concentration breakthrough, with almost no dispersion. The next three sensors show a typical dispersive trend; lower peak, flatter curve, and longer tail. Concerning the concentration values, Sensors 1 and 3 have initial and final negative values, which is not physically possible. This is due to the approximations of the average linear function derived from the calibration data as well as 10% accuracy in sensor readings. For this experiment, after the fifth sensor no more evidence of tracer could be found in the tank. Possible explanations for this phenomenon include: failure of the sensors, heavy dilution of the tracer and no signal detection by the sensors, or the tracer path did not cross certain sensor locations.

The measurements taken from the first five sensors were interesting and showed qualitatively that the wireless sensing equipment could be successfully used to monitor the migration of a plume in a laboratory tank. Equipment-related issues (sensor failure) were identified, pointing out some of the weaknesses of this system. System failure has major implications for field applications. If half the sensors deployed in the field do not respond, much time needs to be devoted to discovering the reason for failure, increasing personnel needed and cost. However, it is anticipated that these issues will be resolved over time, once environmental WSNs are more robust and reliable. For initial deployments, sensor choice and calibration are major considerations that need to be well understood in the laboratory before undertaking larger scale applications.

Experiment 2

Based on the lessons learned from the first tank packing configuration, a number of design improvements were made for the second tank packing. The new tasks consisted in taking manual samples for sensing data validation and obtaining a better sensor calibration function. The goal of this second experimental setup was to compare wireless sensing data with traditional sampling methods to validate this sampling approach.

For this tank packing, a spatially correlated random field was generated using an algorithm based on the turning bands (TBands) method (Mantoglou and Wilson 1982). The spatial distribution of the sands was created with a mean ln K value of 3.5 m/day and a variance of 1.2, and discretized into three ranges corresponding to the three sands used in this experiment (#30, #50, and #70). The tank packing configuration and the sensor placement are given in Fig. 5.

To better mimic field conditions of concentration monitoring in a well in this experimental test bed, a thin plastic casing was mounted around each sensor. Ideally, a well in which the sensor is lowered would be placed in the tank to mimic field conditions. As the sensors are too large in comparison to the dimensions of the tank, a well large enough to fit the size of the sensor would create local flow conditions that would not be truly two dimensional. This casing was approximately 1.5 cm wide, 5 cm large, and 9 cm long. It was important to build the smallest possible casing without impairing the conductivity measurements from the sensors. Decagon engineers established that the conductivity field around the sensor prongs is approximately 1.5 cm in diameter. Therefore wall effects due to the casing are assumed negligible. A stainless steel 250 mesh screen allowed the water flow through the sensor casing. The casing kept the sand grains away from the sensor prongs and the sensors were solely in contact with the pore water. In addition, a thin plastic tube was placed inside the casing to allow for aqueous samples to be extracted for analysis. This design allowed a good approximation to a well setup in a two-dimensional tank.

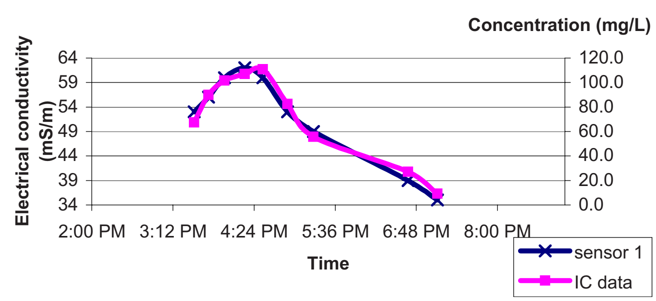

Fig. 6. Breakthrough curve for Sensor 1 with IC data

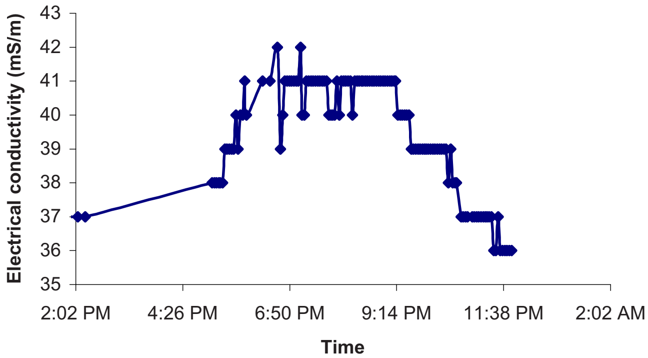

Fig. 7. Breakthrough curve for Sensor 2

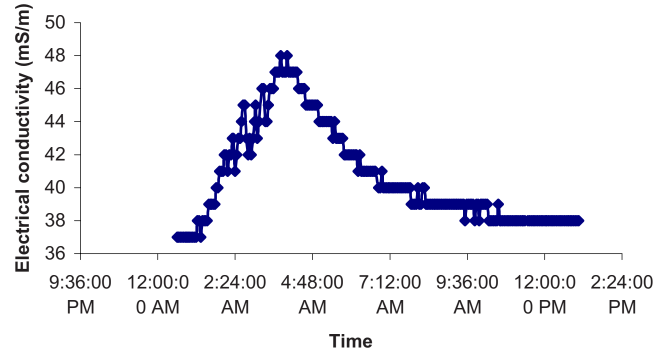

Fig. 9. Breakthrough curve for Sensor 6

The 200 mg/L bromide tracer was injected at the upstream end of the tank in the #30 sand for 40 min. The tracer test was conducted in a similar manner as in the first set of experiments with two major modifications to the monitoring method: wireless sensing protocols were improved for more sophisticated data acquisition, and manual aqueous samples were taken, to be analyzed with the IC. The procedure to take samples was accomplished as follows: the purging volume for each sensor was determined by measuring the length of each tube from the position in the casing to the outlet outside of the tank and calculating the volume of liquid in the tube.

Purging volumes ranged from 4 to 7 mL. Before each sample was taken, water was allowed to drain from the casing by gravity and the volume was measured with a graduated cylinder. During the purging process water in the tube left over from the previous sampling activity was replaced with fresh liquid from the tank. This ensured that the samples taken, accurately represented the amount of tracer passing through a casing during a given time. It was assumed that the entire liquid in the casing was replaced constantly and homogeneously by the tank flow since the casing was screened over its entire length. Once the desired volume was collected and discarded, a 2 mL syringe was used to slowly draw liquid out of the casing and transfer it to a special IC vial. For each sample taken, the time was recorded as well as the sensor reading from the sampled casing. Samples were taken approximately at the same time as the sensor readings.

The tracer reached the tank outlet after about 48 h. A total of 56 samples were collected from the sensor casings. Manual samples were only taken for the sensors which detected a change in electrical conductivity. In addition, samples were taken specifically when electrical conductivity in the tank changed, to capture the breakthrough curve. In other words, the wireless sensing data were used as indicators of tracer concentration changes in the tank over time, and manual samples were taken at these critical times for a more accurate analysis with the IC. The sampling process for the four sensors of interest was interactive with the real-time sensing results. Figs. 6–11 show results for Sensors 1, 2, 6, and 10.

Before starting the tracer test, the base reading for Sensor 1 was measured as 34 mS/m. Therefore, this was considered to be the conductivity value that corresponds to zero bromide concentration. The breakthrough data for the sensor and the IC were superimposed and showed a very good correlation between the two different sets of data. The results for sensors 2, 6, and 10 also show good correlations of data.

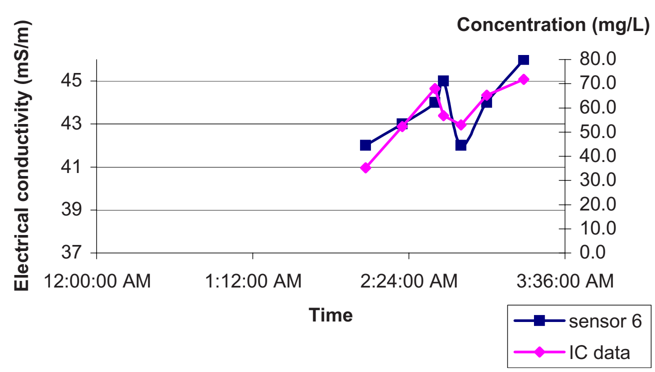

Fig. 10. Selected points from the breakthrough curve for Sensor 6 compared to IC data

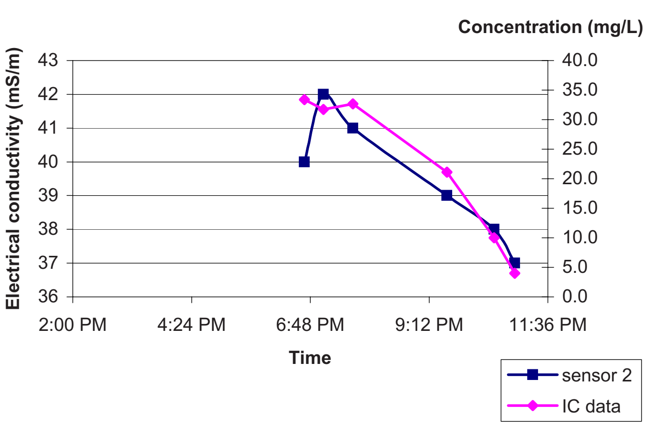

Fig. 8. Selected points from the breakthrough curve for Sensor 2 compared to IC data

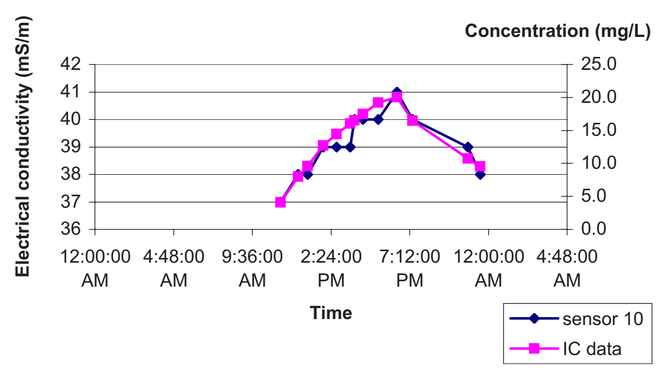

Fig. 11. Breakthrough curve for Sensor 10 with IC data

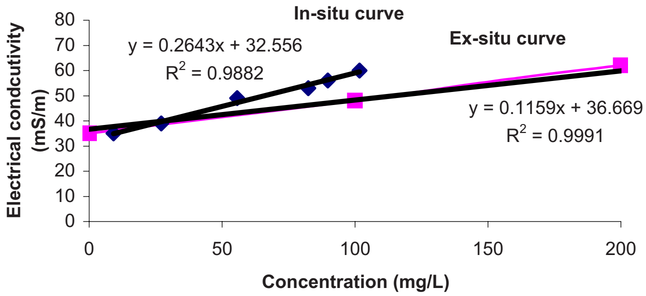

Fig. 12. In situ and ex situ calibration curves for Sensor 1

Sensors 2 and 6 present many fluctuations in the data and were not sampled as often as Sensors 1 and 10. For Sensor 10, the conductivity curve increases in steps, as opposed to a smooth curve for the manual data. It can be observed that the conductivity value does not change before a 3–4 mg/L change in concentration. This means that for every 1 mS/m change in electrical conductivity reported by the motes, the bromide concentration changes by 3–4 mg/L. This observation gives an idea of the sensitivity of the sensor to small changes in concentration. The problem is that the sensors give only readings to the closest mS/m integer, which reduces the resolution of the reading. With a better resolution, more accurate values could be obtained.

Since the manual data corresponded very well to the sensing values, an in situ calibration curve was created for each sensor by plotting electrical conductivity versus concentration. The linear curves gave an R^2 value between 0.7 and 0.9. As an example, Fig. 12 shows the in situ calibration curve for Sensor 1.

The in situ curve is compared to the ex situ curve constructed during the initial sensor calibration outside of the tank. The slope and intercept of both curves are different. The variation could be due to measurement inaccuracies or to inconsistencies in medium characteristics, as was hypothesized earlier. However, it is felt that the in situ graph more accurately represents the true sensor calibration as it was performed in the medium in which the sensor takes the measurements. In addition, the intercept value for the ex situ calibration curve is higher than the lowest value measured in the tank by Sensor 1. In other words, the sensor measurements in the tank are outside of the calibration curve range. Therefore, this curve could not be used for data conversion to concentration data.

Conclusions and Recommendations

The main objectives of this work were (1) to develop a physical test bed to demonstrate the beneficial use of WSNs for contamination detection in groundwater, and (2) to validate the sensor data with a traditional sampling method and to develop effective sensor calibration methods. WSNs have been successfully employed in various fields and they provide many advantages for environmental monitoring applications. The WSNs are especially valuable for environmental monitoring at large scales and in areas where human involvement is impractical or dangerous. In addition, WSNs allow for a connected network of sensors to monitor changes of subsurface groundwater and plume patterns in real time and adaptively modify the frequency of readings. Thus, the field of contaminant hydrology could greatly benefit from this emerging technology. However, before attempting large-scale deployments, laboratory experiments are necessary to better understand the quality of data measured and the potential failure of equipment, and to devise optimal deployment designs.

Many lessons were learned from this laboratory WSN implementation:

1. The choice of sensors is critical. Even though the market for environmental sensors is growing, not many are suitable for long-term applications with minimal human involvement.
2. The various sensor calibration types performed in this work gave different results. Sensor calibration is one of the most crucial components of a WSN deployment. While field calibrations are more complicated than laboratory ones, they more accurately represent the subsurface behavior since the readings are taken directly in the conditions the sensors will be in during the monitoring period. Some sensors on the market come with field calibration options or kits that allow for a solution to be incorporated into the sensor enclosure. Typically, the sensor calibration needs to be performed for each sensor separately because of slight manufacturing divergences. In addition, sensor readings might vary over time (months or years) so that calibrations need to be repeated to capture the change in sensor response. The importance of in situ calibration was pointed out by Ramanathan et al. (2006).
3. The universality of instrument connections is truly a limitation for efficient WSN deployment.
4. During the experiments, sensor failure and data loss due to unresponsive motes or lack of protocol robustness were observed.
5. Because of the ability to obtain high temporal resolution of the sensing data, plume variations can be captured more accurately, and the potential for missing important information on subsurface contamination is decreased.
6. Current sensors do not have a very high resolution and data accuracy. However, manual samples can be taken to obtain higher quality data. A sensor network allows manual sampling to be more focused on the hot spots of the plume, thereby reducing the overall cost of sampling in the field.

As a result, laboratory testing performed in this proof-of-concept study was important to point out the key flaws and challenges associated with WSNs, before field implementations.

Future Work

The work presented is the first step toward developing a new groundwater monitoring technique that promises to improve current data collection techniques in the field. Although it was shown that a simplified WSN system can qualitatively and quantitatively detect a bromide tracer in a short-term laboratory experiment, many improvements need to be made for a robust and reliable field deployment system.

First, a larger laboratory system should be developed to explore the response of the sensors to a more realistic three-dimensional test bed. In a larger test bed, real wells could be installed in which the sensors would be lowered. Wells ensure more flexibility for sensor maintenance: between experiments, the sensors could be removed to minimize data accuracy loss due to biofilm coating on the outside of the sensor, and they could be cleaned and stored in an appropriate solution.

Second, fault detection (e.g., sensor or mote failure) by the motes would be very useful in the field. It would allow the user to assess when recalibration of sensors is necessary or when other technical problems arise. In this work, only single-hop data transmission from each mote directly to the base mote was used. True networks should be created with many motes so that intermediate motes can trigger other motes based on their measurements. In this fashion the plume can be monitored more efficiently.

While the sensors used for this proof-of-concept experiment detect only the electrical conductivity change in water, more sophisticated sensors such as chemical or biological sensors could be used to gather more precise information on the nature of the groundwater contamination. This setup could not only be implemented for plume detection, it could also be left in place after remediation for site monitoring or installed for monitored natural attenuation (MNA).

Last, initial real-time model calibration attempts (not presented in this paper) by integrating wireless data directly into groundwater models and inversion codes showed that at this stage, results were not conclusive. Many hurdles need to be overcome to make this system useful and adaptable to the field. Problems due to sensor and mote failure, numerical model convergence times, and inversion code robustness still limit the applicability of using WSNs in conjunction with models for calibration.

Practical Recommendations for Field Applications

The purpose of this proof-of-concept experiment was to test a WSN deployment in a laboratory setting to assess the feasibility of using this technology in the field. The scope of this work was to develop a technique to help in decision making for remediation of contaminated sites. The small scale laboratory experiments showed that WSNs have a high potential and many advantages for field scale applications in the groundwater contamination field.

1. For long-term monitoring the following must be considered: sensor damage, cleaning, re-calibration, and maintenance in general. Sensor readings change over time as the subsurface affects the material. Some human involvement is always necessary to assure correct functioning of the system.
2. The insertion of sensors in the ground presents several options that need to be carefully researched for the final design. For shallow aquifers, sensors could be directly inserted into the ground with little subsurface disturbance. For deeper aquifers, the sensors might have to be pushed into groundwater wells.
3. Time synchronization on the motes and mote location identification are crucial to keep track of data in the field.
4. Power options must also be considered. Batteries are not practical in the field as they require frequent changing. The most viable solution would be to use a renewable source of energy such as wind or solar, as is already used for many field deployments. Motes can also be "put to sleep" and programmed to "wake up" only when a change in subsurface parameters arises.
5. Deployment design and techniques must be considered. An initial groundwater model based on other types of data such as pumping test results can help in deciding where the sensors should be placed for better results.

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