Automated ground-water monitoring with Robowell--case studies and potential applications

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ABSTRACT

Robowell is an automated system and method for monitoring ground-water quality. Robowell meets accepted manual-sampling protocols without high labor and laboratory costs. Robowell periodically monitors and records water-quality properties and constituents in ground water by pumping a well or multilevel sampler until one or more purge criteria have been met. A record of frequent water-quality measurements from a monitoring site can indicate changes in ground-water quality and can provide a context for the interpretation of laboratory data from discrete samples. Robowell also can communicate data and system performance through a remote communication link. Remote access to ground-water data enables the user to monitor conditions and optimize manual sampling efforts. Six Robowell prototypes have successfully monitored ground-water quality during all four seasons of the year under different hydrogeologic conditions, well designs, and geochemical environments. The U.S. Geological Survey is seeking partners for research with robust and economical water-quality monitoring instruments designed to measure contaminants of concern in conjunction with the application and commercialization of the Robowell technology. Project publications and information about technology transfer opportunities are available on the Internet at URL http://ma.water.usgs.gov/automon/

Keywords: Ground water, automation, water quality, technology transfer

1. INTRODUCTION

An automated ground-water monitoring system named Robowell has been developed, tested, and patented under a grant from the USGS Technology Enterprise Office (TEO) of the U.S. Geological Survey (USGS) [1,2,3]. Robowell provides a method for monitoring ground-water quality that meets accepted manual sampling protocols without incurring high labor and laboratory costs associated with frequent manual sampling efforts. Since December 1994, six prototype monitoring units have been developed and tested. The units have sampled water during all four seasons of the year under different hydrogeologic conditions, well designs, and geochemical environments.

Robowell uses a simple computer to control a pump and a series of electronic instruments, which monitor the quality of ground water that is pumped through the system from a monitoring well or multilevel sampler. The Robowell technology is a representative automated monitoring technology because it is programmed to follow sampling protocols considered necessary for obtaining representative manual samples[4]. In the full implementation, a Robowell system would (1) activate itself as programmed, (2) perform a series of self-tests, (3) measure the water level in the well, (4) calculate the purge volume, (5) measure and record values of water-quality properties and constituents during the purge cycle, (6) determine and record the final values of the properties and constituents, and (7) return to an inactive mode. The system's computer program uses information from system feedback, water-quality measurements, and the internal clock to control the monitoring process automatically. If the system is functioning properly, water-quality properties and constituents are monitored and recorded until purge criteria are met. If equipment errors are detected during a given sampling interval, the system records error codes along with measured values for that sampling interval before returning to the inactive mode. Monitoring operations can be initiated, suspended, or modified in response to errors in system feedback, remote control through a communications link, or direct control by technical staff[2].

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Typically, investigators have lowered monitoring instruments into the screened zone of a well to passively measure water-quality properties in the well under the assumption that these measurements were representative of the quality of water in the surrounding aquifer. The representativeness of passive monitoring results, however, may be affected by well design and local hydrogeology, which are unique to each well site, and by hydraulic gradients and the distribution of solutes in the well or in the aquifer, which may change during the monitoring period. More specifically, data collected by passive water-quality monitoring systems may be affected by borehole-water stagnation, nonuniform flow in the screened zone, and chemical stratification in the screened zone of monitoring wells[2,5,6,7,8]. Therefore, there will always be substantial uncertainty in the representatativeness of passive monitoring results. In contrast, the Robowell technology (if properly implemented in an appropriate monitoring-well installation) minimizes the uncertainty inherent in passive sampling methods by pumping water from the aquifer surrounding the wells using accepted manual sampling protocols.

Measurements made by Robowell indicate changes in ground-water quality on a real-time basis and at a lower cost than for manual sample collection, processing, and analysis. A record of relatively frequent ground-water quality measurements can provide the context for the interpretation of analytical results from periodic discrete samples. Properties such as water temperature, specific conductance, and pH are indicators of ground-water quality and, therefore, changes in these properties indicate changes in ground-water quality[9,10,11]. The monitoring record can be used with analyses of discrete samples to identify the abrupt arrival of a contaminant plume, subtle trends caused by a diffuse source of contaminants, or an analytical error in the analysis of a discrete sample.

This paper, written for the Ground-Water Monitoring Technologies Session of the Environmental and Industrial Sensing Conference of the International Society for Optical Engineering, introduces the Robowell technology, describes the results of case studies, and explores potential monitoring applications. References to existing publications and the USGS technology web pages provide access to detailed information about the technology[1,2,3,10,11]. Case studies illustrate use of and potential value of the Robowell technology. Potential applications are described for the instrumentation engineering community to evaluate monitoring needs that may be addressed using available instrumentation technologies and to identify the need for further development of water-quality monitoring instruments. This publication is sponsored by the USGS TEO to promote technology transfer to other government agencies and the private sector.

2. CASE STUDIES

Robowell has been tested by integration with several ground-water quality investigations conducted by the USGS in Massachusetts. Six case studies were done in cooperation with existing projects to test the unit under different geochemical conditions, establish the practicality of operation in conjunction with hydrologic studies, and to provide information that may be valuable to the studies. The studies provided the opportunity to monitor different water-quality properties and constituents, to assess the performance and durability of different monitoring probes, and to implement advanced communication links between remote field units and customers who are in need of the data.

2.1 Monitoring road salt contamination in ground water

Robowell was implemented as part of a road-salt monitoring study in southeastern Massachusetts to evaluate the representativeness of an existing periodic manual-sampling program[12]. Ground-water quality at the monitoring site was affected by infiltration of high-salinity road runoff from deicing operations during frequent winter storms. It was not known if the monthly sampling program was adequately quantifying seasonal road-salt loads or if short-term variability in ground-water quality would require more frequent sampling to quantify these loads.

The real-time data collected by this Robowell prototype provided the information needed to demonstrate the representativeness of the existing periodic manual-sampling program for determining road-salt loads in ground water at this site. This Robowell prototype was used to monitor ground-water levels and the temperature, specific-conductance, pH, and dissolved-oxygen concentration of ground water pumped from USGS well 414650070360209 during the period from March through June in 1995. The water-level and specific-conductance data collected by the Robowell unit (fig. 1) defined the minimum sampling interval at this site by quantifying the changes in ground-water quality with time. The dissolved-oxygen data (fig. 1) collected by the Robowell prototype provided an unexpected result, as it indicated the effect of oxygen demand in the unsaturated zone. The measured oxygen demand may be caused by transport of an organic deicer (calcium-magnesium acetate) from an adjacent site along the highway by vehicle traffic[13]. Operation of the Robowell prototype at this site indicated the feasibility of the technology in conventional monitoring wells and provided information that was useful to the road-salt monitoring study.

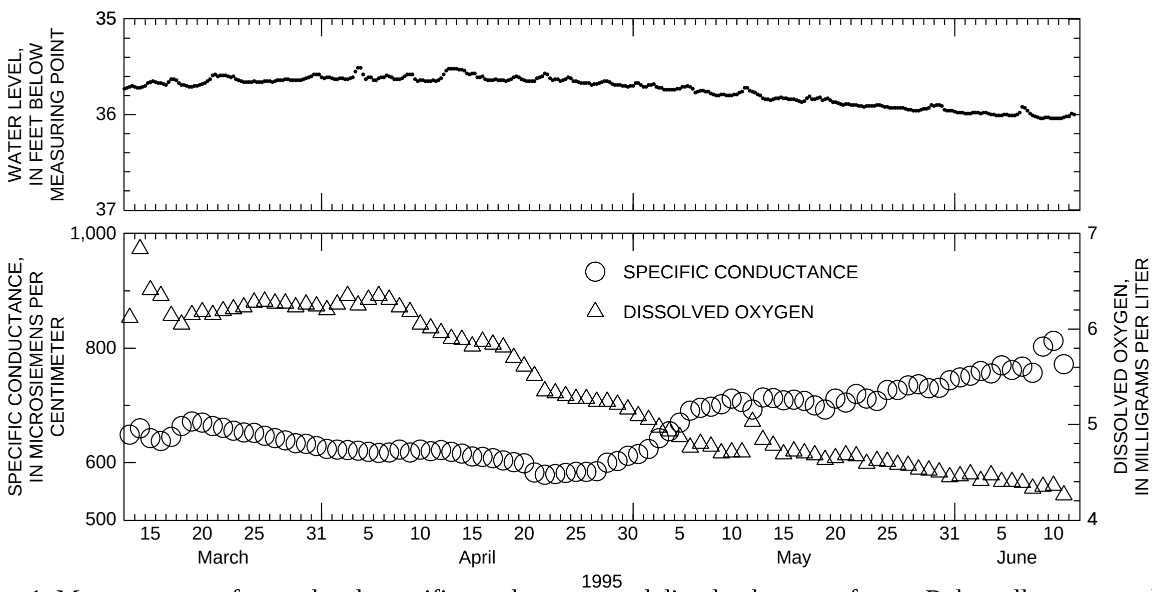

Figure 1. Measurements of water level, specific conductance, and dissolved oxygen from a Robowell prototype that monitored USGS well 414650070360209 during the period from March through June 1995.

2.2 Monitoring natural biogeochemical restoration processes in a sewage-effluent plume

Robowell was implemented to monitor the geochemistry of ground water under a sewage-effluent infiltration bed on Cape Cod, Massachusetts, as part of a study of the natural restoration (also referred to as natural attenuation) of ground-water quality at a treated sewage infiltration site that had been used for 60 years[14]. Abrupt cessation of sewage-infiltration operations at this site provided an opportunity to determine how geochemical environments would evolve and affect contaminant fate and transport after the source was removed. Because little was known about the evolution of geochemical environments under these conditions[14], real-time data were needed to assess the rate of change[15].

The real-time data collected by this Robowell prototype provided the information needed to plan and execute a 3-year sampling program to define the evolving geochemistry at this site. This Robowell prototype was used to monitor the temperature, specific conductance, pH, dissolved oxygen, and turbidity of ground water pumped from 3 ports of a USGS multilevel sampler designated as USGS well numbers 413818070323803, 413818070323806, and 413818070323812 during the period from December 1995 to March 1996. (A multilevel sampler is a well that consists of a number of small-diameter tubes, each ported to a different level in the aquifer.) Three months of data from this device showed that geochemical changes in ground water-quality were gradual and could be characterized by less frequent sampling rounds than had been originally planned[15]. The scaled-back sampling resulted in substantial savings of money and time with no loss of information about the natural restoration process. Operation of the Robowell prototype at this site indicated the feasibility of the technology for multilevel sampling operations and provided information that was useful to geochemical monitoring efforts at this site. In addition, operating difficulties in cold weather led to improvements in subsequent operational designs.

2.3 Monitoring changes in ground-water quality due to sewage-effluent infiltration

Robowell was implemented to monitor the ground-water quality under a sewage-effluent infiltration bed on Cape Cod, Massachusetts, as part of a study sponsored by the TEO. The purpose of this study was to collect the quality-assurance and quality-control data necessary to document the performance of the Robowell technology under remote field-monitoring conditions[10]. Sewage effluent from a treatment plant was released intermittently during the period from June 10 through August 10, 1996. Effluent from a process of liming and pressing residual solids from the facility was released intermittently during the period from September 25 through November 23, 1996. These releases caused two distinct plumes of sewage effluent in the ground water beneath the bed. The Robowell prototype was installed in wells near the infiltration site to monitor the geochemical effects of the two releases from the treatment-plant during this sewage-effluent release period.

The combination of automated monitoring data, manual check measurements, and samples collected for laboratory analysis provided data needed to evaluate the Robowell technology and for examining the effects of sewage effluent on ground-water quality[10]. This Robowell prototype was used to monitor ground-water levels in USGS well 413822070324601, and the temperature, specific conductance, pH, dissolved oxygen, and dissolved ammonium in ground water pumped from USGS wells 413822070324601 and 413822070324602 during the period from May through November, 1996. Effects of the sewage release and the subsequent sludge-press-effluent release on ground-water quality are apparent in the changes in the measurements of specific conductance, pH, dissolved oxygen, and ammonia concentrations in well 413822070324601 (fig. 2). Specific conductance more than doubled--from about 200 to more than 500 microsiemens per centimeter at 25 degrees Celsius (µS/cm)--when the first plume infiltrated to the water table in June 1996 and increased by an order of magnitude--to a range from about 2,000 to about 7,000 µS/cm--when the second plume arrived in October 1996. Measurements of pH increased from 5.5 to 6.0 standard units when the first plume arrived, and increased to almost 9 standard pH units when the limed sludge-press water reached the water table. In each case, measurements of dissolved oxygen (fig. 2) showed an initial increase before the arrival of the dissolved solids as oxygenated water in the unsaturated zone infiltrated to the water table, and then a steady decrease to zero as microorganisms utilized available oxygen to consume the sewage[10]. The sewage plume contained substantial concentrations of nutrients. The nitrogen species were under geochemical control and were partitioned between elemental nitrogen, nitrate, nitrite, ammonium ion and dissolved ammonia[10]. Therefore, the water-quality probe readings for ammonium were more suitable for measuring the geochemistry of the system than for determining total nutrient concentrations in the sewage plumes because these readings do not reflect the total nutrients in ground water. In summary, the automated monitoring record provided a very detailed picture of the changes in ground-water quality in real time. During this time, remote access to the data record by means of phone-modem communications facilitated manual sampling efforts to verify the automated monitoring records. Robowell successfully characterized ground-water quality in the new plumes, as they were formed[10].

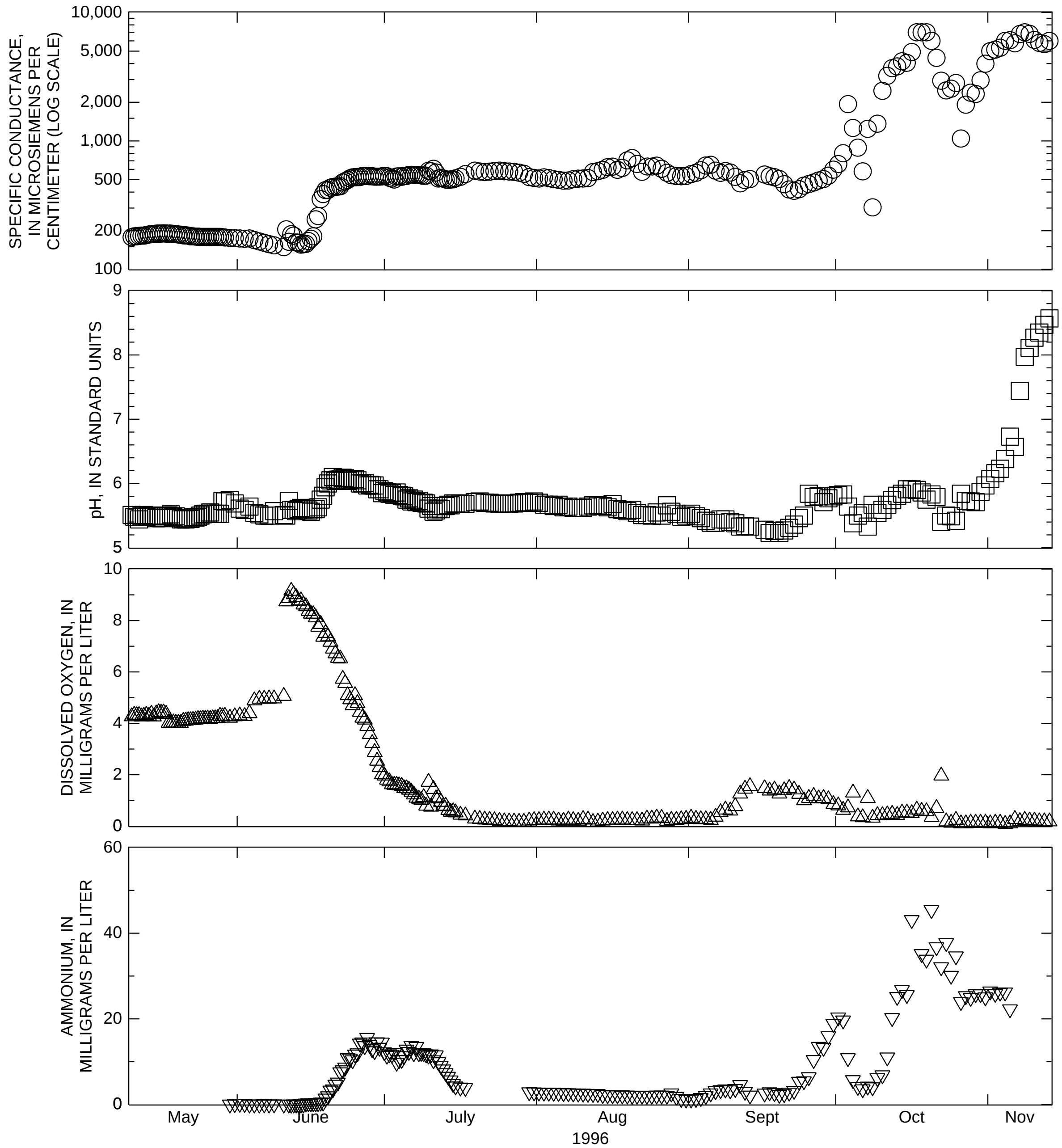

Figure 2. Measurements of specific conductance, pH, dissolved oxygen, and ammonium from a Robowell prototype that monitored USGS well 413822070324601 during the period from May through November 1996.

2.4 Monitoring changes in ground-water quality due to an experimental remediation technique

Robowell was implemented to monitor changes in ground-water quality on Cape Cod, Massachusetts, as part of a study to evaluate the effectiveness of an experimental in situ reactive-wall remediation[11]. Investigators injected materials including iron filings and a guar slurry to form a permeable zero-valent iron wall in the path of a contaminant plume. The highly reducing environment of the wall was expected to enhance abiotic degradation of hydrocarbons in ground water. Investigators sponsored the use of the Robowell technology at this site to determine when geochemical changes could be measured in a monitoring-well array downgradient of the reactive wall and to monitor the variations in water quality once the plume of reaction byproducts arrived in these wells.

The real-time data collected by this Robowell prototype provided the information necessary to characterize ground water quality at the site and provided a context for the interpretation of the results of laboratory analyses of samples collected in the adjacent well cluster. The monitoring effort successfully demonstrated the ability of the technology to act as a sentry to detect the arrival of contaminants in ground water[11]. Robowell was used to monitor ground-water levels and the temperature, specific conductance, pH, dissolved oxygen, and oxidation-reduction potential (ORP) of ground water pumped from USGS well 414047070321304 during the period from June 1998 to July 1999. The Robowell prototype recorded substantial changes in ground-water quality in a matter of days. The reaction byproducts of the reactive wall and a subsequent enzyme and pH adjustment to the reactive wall eventually raised pH by almost a full unit, raised specific conductance by about 800 µS/cm, and completely depleted the dissolved oxygen in the aquifer in the vicinity of the well[2,11]. Robowell was successful as a sentry in this application because it notified the project chief that geochemical changes had been detected by calling her office telephone with the voice modem. These voice modem alerts (preprogrammed messages in English) on her telephone answering machine and subsequent telephone access to the real-time data by telephone allowed the project chief to optimize manual sampling efforts and minimize laboratory-analysis expenditures. This sampling program was optimized because the project chief could dispatch sampling teams to the remote site when the plume arrived and when there was a substantial change in measured ground-water quality.

2.5 Monitoring septic-system effluent in ground water

Robowell was implemented as part of a study to determine the source of nutrients causing eutrophication of Walden Pond in Concord, Massachusetts[16]. This Robowell prototype was used to monitor changes in ground-water quality caused by effluent from the septage leach field for the public bathhouse at Walden Pond State Park. Investigators cosponsored the use of the Robowell technology at this site to determine short-term and seasonal variability in ground-water quality caused by variations in septic-system effluent from the public bathhouse.

The real-time data collected by this Robowell prototype provided the information necessary to evaluate and modify the ground-water sampling array as the direction of ground-water flow changed with regional declines in ground-water levels. Robowell monitored ground-water levels and the temperature, specific conductance, and pH of ground water pumped from USGS well 422627071195901 during the period from August 1998 through August 1999. The prototype also measured air temperature and relative humidity, which are needed to refine estimates of evaporation from the lake and to estimate ground-water recharge rates in the local drainage basin. Substantial decreases in measurements of specific conductance and water levels during August and September 1998 (fig. 3) indicated that the direction of ground-water flow was changing. These results were surprising, given the fact that August and September are months with heavy use of the bathhouse facilities and thus high effluent loading rates from the septic system. Increased manual ground-water level monitoring in the area and installation and sampling of new wells at this site confirmed that the direction of ground-water flow had changed and that the Robowell prototype was now on the edge, rather than in the center, of the plume of septic-system effluent. The data from Robowell and from manual sampling indicated that the effluent plume was traveling toward the pond, which prompted seepage studies at the edge of the pond to detect the arrival of this plume. Unfortunately, site constraints and logistical limitations precluded redeployment to the new wells or addition of the new wells to the Robowell monitoring program. This Robowell prototype, however, continued to provide information about ground-water levels and ground-water quality affected by the sewage plume from its original location.

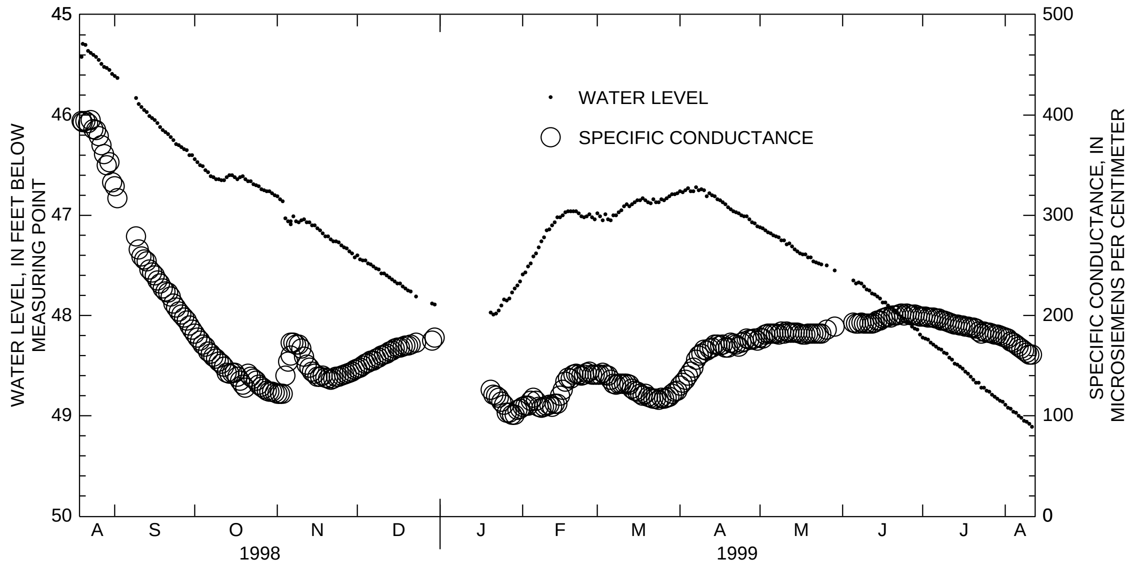

Figure 3. Measurements of water level and specific conductance from a Robowell prototype that monitored USGS well 422627071195901 during the period from August 1998 through August 1999.

2.6 Monitoring saltwater intrusion in public water-supply well fields

Robowell was implemented for monitoring the temporal variability in the quality of water in wells screened near the freshwater-saltwater interface in Truro, Cape Cod Massachusetts[17]. This Robowell prototype was implemented in cooperation with the Provincetown Water Department, the TEO, and a USGS water-resources study on the lower Cape Cod aquifer system. This project was designed to assess the suitability of the technology for monitoring movement of the freshwater-saltwater interface in ground water and to implement and test methods for providing real-time data from ground-water monitoring to the public on the Internet.

The real-time data collected by this Robowell prototype are being used to monitor the movement of the freshwater-saltwater interface in the aquifer in relation to measurements of regional ground-water levels in relation to seasonal pumping rates at a local public-water-supply well field. This Robowell prototype is currently monitoring ground-water levels in USGS well 420244070060601 and the temperature, specific conductance, and pH in ground water pumped from USGS wells 420244070060601 and 420244070060602 during the period from January 2000 through the present. Graphs of water levels, specific conductance, and pH are available to the USGS, town water managers and the public on the Internet[17]. Operational parameters, including equipment-shelter air temperature and humidity, battery voltage, bladder-pump gas pressure and flow rates, and diagnostic error codes are available to the operators on the USGS intranet. The on-line graph of hourly water-level measurements shows the daily tidal cycles, the effect of large storms on areal recharge, and seasonal changes in ground-water levels at this coastal site[17]. The on-line graph of specific-conductance values measured during the pumping cycles (that occur twice a day) indicates that winter recharge during the monitoring period did not substantially change the position of the freshwater-saltwater interface before the summer tourist season necessitated increased withdrawals from the well field. The on-line graph of pH measured during the pumping cycles qualitatively indicates that the salinity in each well may come from a different intrusion source; the measured pH does not increase with higher conductance as would be expected for the mixing of low-pH freshwater and relatively high-pH seawater at this site[17]. The data from this Robowell prototype provides a direct indication of aquifer heads, which theoretically control the position of the interface and indicate water quality in the screened zones of the monitoring wells. These data also are being used to plan geophysical monitoring efforts and to interpret the results from geophysical measurements at this site. The fact that specific conductances measured in the upper well (about 18,000 µS/cm) are higher than in the lower well (about 9,000 µS/cm) helps to confirm the interpretation that the pumping wells are drawing in saltwater in a local lateral-intrusion plume above a clay bed situated between the wells and the underlying regional freshwater-saltwater interface[18]. The Robowell data were also compared to data provided by a passive-monitoring system (conductance probes installed in the screened zones of adjacent monitoring wells) and to data from manual sampling efforts in these monitoring wells. Cooperative experiments by the USGS, the Provincetown Water

Department, and their contractor revealed the inadequacy of this passive-monitoring design. These experiments prompted conversion of the system to the Robowell technology under an agreement for technology transfer between the town, their contractor, and the USGS TEO.

3. POTENTIAL APPLICATIONS

The Robowell technology may be well suited for monitoring applications beyond the scope of the existing case studies, which represent successful monitoring efforts for many different contaminant sources. For example, the USGS New Hampshire-Vermont District is currently planning to use the Robowell technology to detect the chemical byproducts of blasting activities in water from bedrock wells near construction sites. Monitoring opportunities for use of the Robowell technology, however, have so far been limited by the scope of active studies and monitoring sites available to researchers in the USGS Massachusetts-Rhode Island District. Improvements in the capabilities of water-quality sensors to quantitatively measure many constituents of interest and reduction in unit cost of new sensors are necessary to expand the applicability of the Robowell technology. A review of the literature, however, indicates that instruments for monitoring basic water properties and constituents--currently available for use with the Robowell technology--may be sufficient for improving water-quality monitoring efforts at many sites. Several studies indicate that standard measurements of water-quality properties and constituents may be used to detect changes in ground-water quality in areas affected by urban and suburban septic and stormwater infiltration, municipal-landfill leachate, or infiltration from chemical spills, chemical disposal sites, and waste sites for military munitions.

Urban and suburban septic and stormwater infiltration may have substantial effects on the quality of water available to public and private ground-water supplies. For example, a study that determined contributing areas to public-supply wells noted a significant correlation between nutrient concentrations in the water supply and the calculated percentage of the pumpage contributed by areas with high housing densities[19]. Another study used measurements of specific conductance and chloride to determine the relative effects of road salting and septic effluent on ground-water quality for different housing densities[20]. A study of the effects of land use on ground-water quality detected statistically significant increases in specific conductance and inorganic and organic contaminants with increasing land-use intensity[21]. Land-use studies, however, commonly compare differences in water quality between wells at different sites rather than variations in water quality at individual sites. Intersite comparisons introduce site-specific variability in relations between water-quality properties and contaminants of interest that may be developed for individual dedicated monitoring systems.

There is considerable interest in the potential for using the Robowell technology in sentry-well applications for monitoring potential leakage at municipal landfill sites, chemical spills or chemical disposal sites, and waste sites for military munitions[22, 23]. Several USGS studies in different geological, hydrological and geochemical environments including studies in Florida[24], Kansas[25], Maine[26], Missouri[27], Oklahoma[28], and Tennessee[29] provided information indicating that measurements of water-quality properties and constituents may be useful in detecting the presence of municipal-landfill leachate in ground water. The study in Kansas included information about the quality of landfill leachate and about degradation processes that may affect ground-water quality[25]. This report indicated that the specific conductance of undiluted landfill leachate was expected to be between 6,000 and 9,000 µS/cm[25], which is much higher than the specific conductance of fresh ground water[9]. This report also indicated that biochemical reaction of constituents in the leachate would be expected to cause measurable changes in pH, dissolved oxygen, ammonia, and other measurable properties and constituents[25]. In another example, specific conductance qualitatively covaried with several inorganic and organic contaminants in ground-water samples collected from different wells at a Superfund site in Massachusetts[30]. Similarly, a USGS study at a munitions waste site at the Aberdeen Proving Grounds in Maryland provided information indicating that measurements of water-quality properties and constituents may be useful in detecting the presence of contaminants in ground water at these sites[31].

There are many potential applications for the Robowell technology. Results from the existing case studies and information provided in the literature indicate that the Robowell technology may be effective for monitoring the flow and quality of ground water at many sites. The studies cited above, however, were designed to characterize the hydrogeology and ground-water quality at contaminant sites, not to evaluate surrogate parameter relationships for contaminants of interest. Therefore, further studies are required to establish the suitability of the Robowell technology for monitoring different sources of contaminants under different hydrogeologic conditions. Furthermore, regulators and decisionmakers commonly want direct measurements of the regulated constituents of concern, so research is needed to develop water-quality-monitoring instruments that can be used with Robowell to economically and quantitatively measure these contaminants[23].

4. CONCLUSIONS

Real-time monitoring can provide information about short-term variability, seasonal effects, and long-term trends in contaminant concentrations if coupled with appropriate sampling designs to collect calibration samples for laboratory analysis. The Robowell technology may also be suitable as a sentry to document changes in water quality, aquifer heads, and flow directions. Robowell can provide timely information by voice-modem contact, direct data-modem connection, or by links to the Internet when conditions change. Research is needed to further explore applications of the Robowell technology at different sites and with robust and economical water-quality-monitoring instruments designed to quantitatively measure the concentrations of selected contaminants. The USGS TEO is actively seeking technology-transfer opportunities with local state and federal governments, the academic community, and private industry to promote this and other USGS technologies.

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