Robowell: A reliable and accurate automated data-collection process applied to reactive-wall monitoring at the Massachusetts Military Reservation, Cape Cod, Massachusetts

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ABSTRACT

Robowell was developed and tested by the U.S. Geological Survey (USGS) to automatically monitor ground-water quality. Robowell follows standard manual-sampling protocols that require monitoring and recording of properties and constituents in water pumped from a well or multilevel sampler until purge criteria have been met. The Robowell process can be used to identify changes in ground-water quality on a real-time basis without the cost of sample collection, processing, and analysis. This automated process can be tailored for different applications.

Six Robowell units have reliably sampled water in different well designs and geochemical environments during all four seasons of the year since 1994 to produce accurate real-time ground-water-quality records that are more than 96 percent complete. Performance has been verified with a program of regular quality-control samples obtained by using independent water-quality probes, manual measurements, and laboratory analyses throughout the period of record. Results of the quality-control program indicate that from 80 to more than 95 percent of the measurements of specific-conductance, pH, and dissolved-oxygen would be rated as good or better on the basis of draft USGS guidelines for water-quality measurements. These results verify the integrity of the automated-sampling records and demonstrate that the automated monitoring system can accurately measure ground-water quality over a large range of geochemical conditions.

A Robowell technology demonstration unit was installed and run on Cape Cod at the Massachusetts Military Reservation with the assistance of the USGS Toxic Substances Hydrology Research group. This unit was run to test the technology and to monitor geochemical changes caused by emplacement of a zero-valent, iron reactive wall designed to remediate volatile organic compounds in ground water. The monitoring unit recorded substantial changes in ground-water quality in a short period as the reaction byproducts of the wall and a subsequent enzyme/pH adjustment raised pH by almost a full unit, raised specific conductance by about 800 µS/cm (microsiemens per centimeter at 25 degrees Celsius), and completely depleted the dissolved oxygen in water from the well. The automated monitoring system demonstrated its success as a sentry well by notifying the project chief through phone calls from a voice modem that geochemical changes had been detected. Real-time records at the site define the variability in ground-water quality during the monitoring period.

INTRODUCTION

Most of the costs involved in operating a ground-water monitoring network are associated with labor and the materials required for manual water-sample collection (Zhou, 1996). Minimizing the cost of ground-water monitoring programs by using statistical strategies to reduce sampling frequency may result in data that are inadequate to (1) determine representative mean (or median) values of water-quality properties and constituents; (2) detect long-term trends, periodic fluctuations, and abrupt changes in water quality; and (3) verify the accuracy of the resulting estimates of the trends (Johnson and others, 1996; Zhou, 1996). Process automation is an alternative to manual methods, but searches of the literature, ground-water-monitoring equipment supply catalogs, and patent records did not reveal any automated monitoring devices or processes that meet currently accepted ground-water-quality sampling protocols.

The complexity of the search for an appropriate automated monitoring system is compounded by long-standing debates about appropriate ground-water-monitoring protocols. Debate about the proper sampling methods and protocols appropriate for a given site will always exist because the ground water and aquifer materials surrounding each monitoring well have unique physical and chemical characteristics that can change through time. Sampling equipment and purging protocols appropriate to a site are necessary to obtain consistent measurements that are representative of aquifer-water quality (Herzog and others, 1991; Koterba and others, 1995; Stone, 1997). Therefore, to obtain consistent and representative measurements, automated monitoring techniques ideally would follow the same protocols selected for manual sample collection. Historically, automated ground-water-quality monitoring has been done using passive monitoring devices, but these devices do not collect data using methods that are comparable with manual-sampling protocols. Thus, the comparability of the passive-monitoring record obtained from an automatic-monitoring probe and the results of analysis of water samples obtained from a well is uncertain (Smith and Granato, 1998).

The U.S. Geological Survey (USGS) developed a process and assembled prototype sets of instrumentation and equipment that can be used to automatically monitor ground-water-quality properties and constituents using established sampling protocols. The technology was developed under a grant from the USGS Technology Enterprise Office, and a patent is pending on the process and device (Granato and Smith, 1998). This automated monitoring system provides data that are consistent with results of analysis of ground-water samples collected manually. Robowell was designed to monitor ground-water quality in real time and to provide the operators with the information needed to optimize manual sampling efforts at a ground water monitoring site. This paper briefly describes this automated process, documents results of a quality-assurance and quality-control (QA/QC) program, and presents a case study done with the assistance of the USGS Cape Cod Toxic Substances Hydrology Research Group.

ROBOWELL: THE PROCESS

Robowell is an automated process that was developed and tested by the USGS to provide 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. The process embodies a series of programmed instructions that activate the equipment on a preset schedule to monitor and adjust the status of the system as it purges the well and records measurements. If the system is functioning properly, water-quality properties and constituents are monitored and recorded until purge criteria are met. An example of one implementation of the Robowell process is shown in figure 1. Typically, a system using the process 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. If errors are detected, the system records error codes along with measured values for the sampling interval before returning to the inactive mode. The system's computer program uses information from system feedback, water-quality measurements, and the internal clock to automatically control the process. Normal operations can be suspended or modified in response to errors in system feedback, remote control through a communications link, or direct control by technical staff maintaining the system.

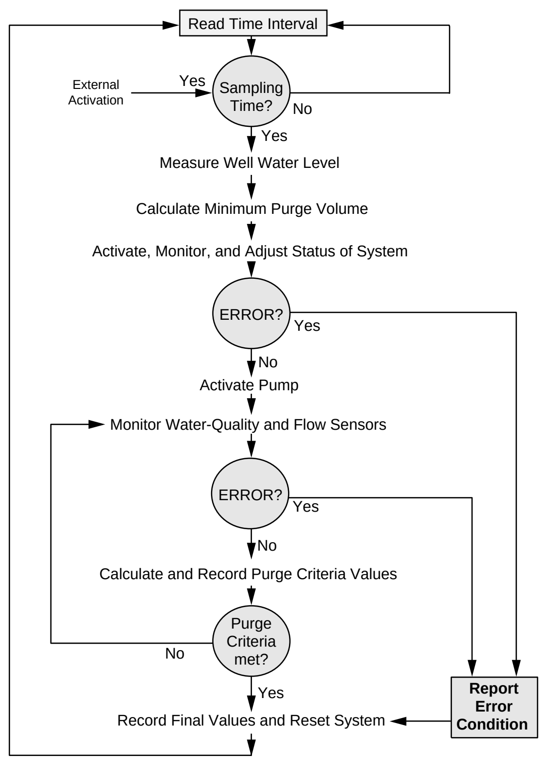

Figure 1. Generalized example of a process flow chart for the Robowell automated ground-water monitoring system.

The Robowell process is an improvement over passive automated ground-water-monitoring systems because measurements made by Robowell are directly comparable to measurements made by manual sampling. Information from periodic manual sampling events during a comparative test of active and passive automated monitoring methods indicates that passive measurements may be substantially biased in relation to measurements made using standard manual-sampling protocols, even in short-screen water-table monitoring wells (Smith and Granato, 1998). Unlike passive monitors, Robowell pumps and purges the well or multilevel sampler while measuring values of each prespecified water-quality property and constituent until standard purge criteria (Herzog and others, 1991; Koterba and others, 1995) have been met. Additionally, all measured values are recorded during the purge cycle to document that final recorded values are representative of water in the aquifer.

The Robowell process can be used to detect changes in ground-water quality on a real-time basis and at a lower cost than that required for manual sample collection with subsequent processing and analysis. Properties such as water temperature, specific conductance, and pH are indicators of ground-water quality (Hem, 1992) and, therefore, changes in these properties indicate changes in ground-water quality. A record of relatively frequent measurements of water-quality properties and(or) constituents made at a ground-water monitoring site can provide the context for the interpretation of periodic discrete samples collected for laboratory analysis. The record can be used with the discrete samples to identify an abrupt arrival of a contaminant plume, trends caused by a diffuse source of contaminants, or an analytical error in a discrete sample analysis. Detection of substantial changes in measured values by remote query can prompt a visit to the field installation for manual measurements. Independent manual field measurements and recalibration of the monitoring probes with a separate measuring device resets the system and further verifies recorded values. If changes in water quality are substantiated by calibration and independent manual field measurements, a sample can be collected for further documentation by laboratory analysis. The automated process can supply information needed to decide when the collection of a water sample for laboratory analysis would best meet the objectives and the QA/QC design of the monitoring effort.

The automated process is designed so that it can be tailored for different applications. Purge criteria appropriate for different types of chemical constituents, sampling installations, and hydrogeologic regimes (Robin and Gillham, 1987; Herzog and others, 1991; Koterba and others, 1995) can be used, and changes in purge criteria can be accommodated as new ground-water-sampling information becomes available.

The process is designed so that commercially available sampling equipment and instrumentation can be selected on the basis of the nature of the contaminants to be measured, the hydrogeology of the site, and site logistics such as available power and communications (Granato and Smith, 1998). Also, the process--if operated from a local base station--can be used to monitor one or several closely spaced wells or multilevel sampling ports. The instruments and equipment typically used to implement the process at research sites are more complex than would be necessary for some applications. The system typically includes a Campbell Scientific Incorporated (CSI) CR10 data logger[1] as the control module for the process and a CSI SM192 solid-state storage device to store data. Because electric and phone services typically are not economically feasible at field sites, batteries recharged by solar panels are used to power the controllers and other instruments, nitrogen gas is used to inflate a packer each time the system is activated and to power the QED bladder pumps through a pneumatic logic controller, and a CSI DC112 telephone modem is used for communications. The water level in the water-table well is monitored with a Keller pressure transducer (operating range of 0-0-2.5 pounds per square inch). A hand-operated Plastomatic three-way valve is placed near the beginning of the flow train to divert water for manual collection of samples. A 1/2-inch Data Industrial flow sensor is used to monitor the flow rate of ground water pumped through the system during purge and recording cycles. A Hydrolab Multiprobe, with a flow cell, is used as a control module for the water-temperature, pH, specific-conductance, and dissolved-oxygen probes under data-logger control. For some applications, however, the process could be implemented with only a dedicated pump, a conductance probe, and a simple data logger using solar/battery power.

ROBOWELL: A RELIABLE AND ACCURATE DATA-COLLECTION PLATFORM

Six Robowell monitoring units have been in operation at one time or another since December, 1994. The units have sampled water during all four seasons of the year under various hydrogeologic conditions, well designs, and geochemical environments. In total, the six units have operated reliably for more than 881 days to produce data that were consistently verifiable when manual check measurements were performed. During these sampling periods, the units were not in operation an additional 30 days because of technical difficulties. These 30 days represent only about 3.4 percent of the period of record. About 14 of these days of lost record occurred during the operating period for the second unit and were caused by freezing conditions. Design changes in the subsequent prototypes have resolved this problem.

When each prototype is emplaced and activated, a series of QA/QC measures is initiated to ensure that the system is collecting valid measurements that are equivalent to measurements obtained by accepted manual sampling methods. Each system is constructed of inert materials that have been demonstrated to be appropriate for constituents of interest. The components of each system are washed, acid-leached, and rinsed with deionized water to ensure that the system is thoroughly clean before installation. Equipment blanks are analyzed to ensure that the system is not contributing constituents of interest to the water sampled. Once the system is emplaced, the water-quality probes are maintained by performing precalibration measurements with standard solutions, cleaning and maintaining probe components, and recalibrating with attention to changes in the slope and intercept of probe calibration data.

A program of regularly collected quality-control (QC) samples obtained by using independent water-quality probes, manual measurements, and laboratory analyses is necessary to demonstrate the accuracy and precision of the data collected. Results of the QC program for the specific-conductance measurements (fig. 2) demonstrate that the automated method produces valid, accurate, and precise measurements when compared to traditional manual measurements. Examination of the specific-conductance measurements reveals that 93 percent of the 44 QC samples were within ±5 percent and 95 percent of QC samples were within ±10 percent of manual and laboratory

[1] The use of brand/firm/trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

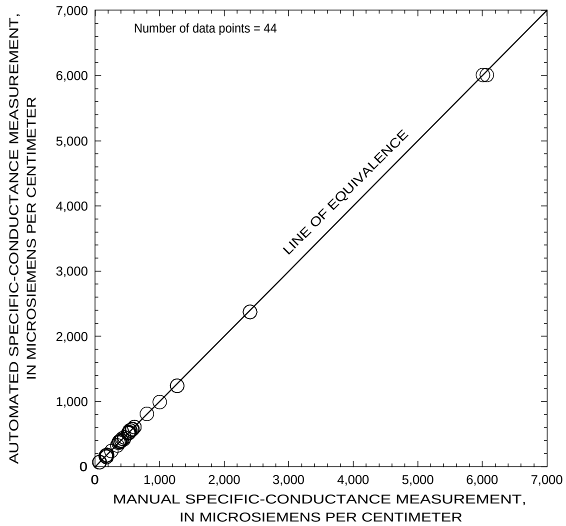

Figure 2. Relation between automated and manual quality-control measurements of specific conductance from several automated ground-water-quality monitoring stations in Massachusetts.

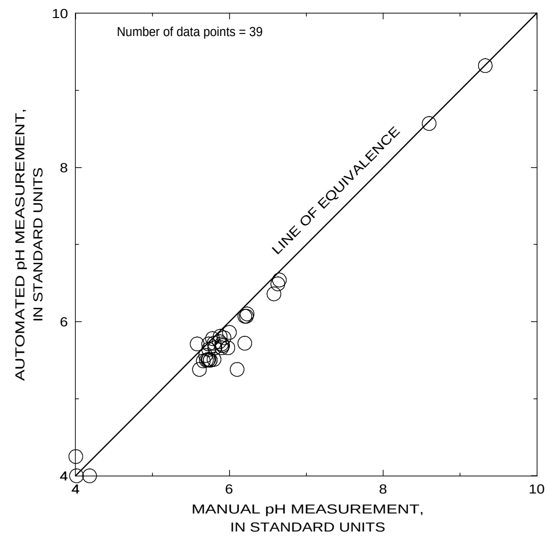

Figure 3. Relation between automated and manual quality-control measurements of pH from several automated ground-water-quality monitoring stations in Massachusetts.

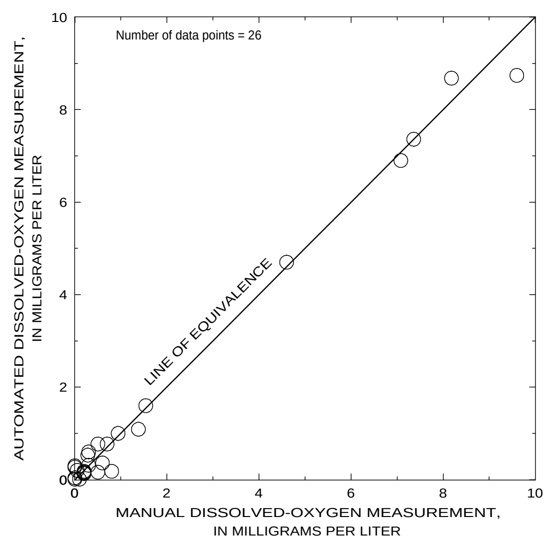

Figure 4. Relation between automated and manual quality-control measurements of dissolved oxygen from several automated ground-water-quality monitoring stations in Massachusetts.

measurements. These specific-conductance values would be classified as "excellent" and "good," respectively, as defined by USGS draft water-quality record ratings (H.C. Mattraw, USGS, written commun., 1998). Results of the QC program for pH measurements also indicated that that the accuracy and precision of automated measurements were equivalent to those of manual sampling efforts (fig. 3). These 39 QC measurements reveal that about 70 percent of all pH measurements were within ±0.2 pH units (an "excellent" rating by USGS draft guidelines, and the published accuracy of the probe) and 97 percent were within ±0.5 pH units of manually obtained values (a "good" rating by USGS draft guidelines). Manual measurements of pH consistently were slightly higher than those made by the automated system. The lower automated pH measurements may be an artifact of sampling in a flow cell. The automated measurements, however, may be more accurate than the manual measurements because the water in the flow train cannot degas to the atmosphere during the measurement process. The QC program for dissolved-oxygen (DO) included 26 measurements. Results indicated the accuracy and precision of individual automated measurements were equivalent to those of manual sampling efforts (fig. 4). For DO measurements, the USGS draft guidelines define uncertainty ranges of ±5, ±10, and ±15 percent as "excellent," "good," and "fair," respectively. These classifications do not apply for values of less than 1.0 because the accuracy of most commercial DO probes is within ±0.2 mg/L (milligrams per liter). Of the population of DO measurements greater than 1.0 mg/L (n=7), about 57 percent and 85 percent of measurements would be rated "excellent" and "good," respectively. Below a DO threshold of 1 mg/L (n=19), 61 percent of measurements were within ±0.2 mg/L (the uncertainty range of the probe), and 99 percent were within ±0.4 mg/L. By extension of the pH rating method, this means that 61 percent of these DO readings can be rated "excellent" and 99 percent can be rated "good" or better. Therefore, the QA/QC program ensures that the automated monitoring system can produce data that are as valid, accurate, and precise as comparative manual measurements. The automated system, however, can produce a detailed, real-time data record with many more individual measurements than could be obtained by manual sampling methods, which are limited by cost and personnel constraints.

Results of the QA/QC program verified the integrity of the automated sampling records and demonstrated that the automated monitoring system can accurately measure ground-water quality over a large range of geochemical conditions. Specific conductance in the QC samples ranged from about 70 to about 6,000 µS/cm, and real-time specific conductance measurements ranged from about 60 to about 8,250 µS/cm. Thus, the automated monitoring system operated successfully over a range of specific-conductance values of about two orders of magnitude, which represents the full range of ionic strength for fresh and brackish waters commonly analyzed in water-quality monitoring studies (Hem, 1982; Hem, 1992). The values of pH measured in the QA/QC program and the automated monitoring records ranged from about 4 to about 10.6 standard units. By comparison, pH values in most ground waters measured across the United States generally range from about 6.0 to about 8.0 (Hem, 1992). The automated monitoring records and the QA/QC program demonstrated that the automated monitoring system provides acceptable data over a dissolved-oxygen concentration range from nearly anoxic to nearly saturated conditions (0-8.7 mg/L). The automated monitoring system, therefore, provided accurate data over the full range of water-quality conditions expected for most ground-water-quality monitoring conditions.

CASE STUDY: REACTIVE-WALL MONITORING

A Robowell prototype was installed on Cape Cod at the Massachusetts Military Reservation (MMR) to augment and guide manual sampling and to provide a demonstration unit for the technology development process. The site is favorable for a short-term ground-water-quality investigation because the unconsolidated deposits of sand and gravel in the area form a permeable, unconfined aquifer. Expected changes in ground-water quality caused by an experimental in situ ground-water-treatment method known as the reactive wall, or the zero-valent iron wall (Hubble and others, 1997; Hubble and Gillham, this volume) would provide specific geochemical events to be monitored, and the automated monitoring prototype could provide the research team with real-time information with which to plan and implement sampling events. The automated monitoring unit was emplaced using a 2-inch-diameter polyvinylchloride well that was screened from about 99 to 101 ft (feet) below land surface at a site where the water table was about 80 ft below land surface (USGS well SDW 485-102A). This well is about 30 and 50 ft downgradient from the first and second reactive walls, respectively (Hubble and Gillham, this volume).

The reactive wall was emplaced by the MMR Installation Restoration Program (IRP). The reactive zero-valent iron wall technology consists of iron filings and a guar slurry that is injected at high pressure to form a permeable wall in a specified zone of the aquifer (Hubble and others, 1997; Hubble and Gillham, this volume). The presence of the zero-valent iron is expected to create a highly reducing environment, altering the existing ground-water chemistry and microbial population to enhance abiotic degradation of the hydrocarbons. Theoretically, as the plume moves through the permeable reactive wall, the zero-valent iron will become oxidized and reductively dechlorinate the organic compounds, producing water, hydrogen, chloride, and aliphatic hydrocarbons, such as methane and ethane, which are considered to be harmless in low concentrations (Hubble and others, 1997; Hubble and Gillham, this volume).

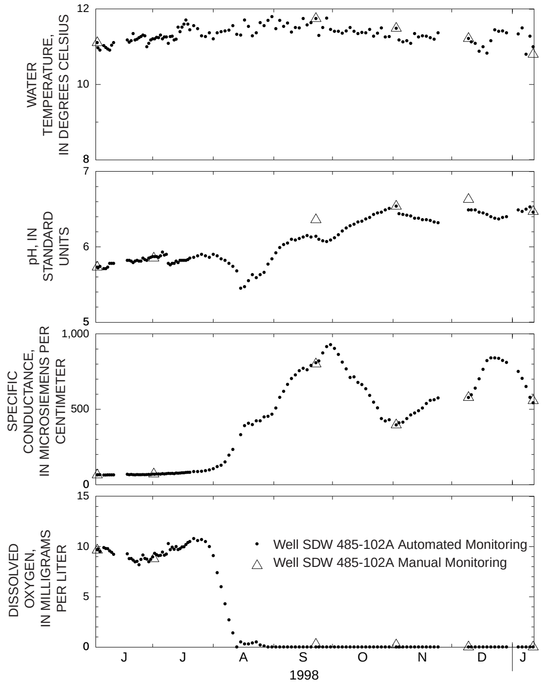

Figure 5. Ground-water quality properties measured with the automated monitoring process and manual measurements in well SDW 485-0102A, downgradient from the reactive wall, Cape Cod, Massachusetts.

Contractors for the IRP have installed two prototype walls in series in the aquifer within a plume that originates from a chemical spill source area on the MMR (Savoie and Granato, 1998). These walls are designed to be about 50 ft wide and to intercept the vertical extent of the plume from about 80 ft to about 140 ft below ground surface. The USGS, through its Toxic Substances Hydrology and National Research Programs, with cooperation from the U.S. Air Force Center for Environmental Excellence and the University of Waterloo, is studying the effects of the zero-valent iron on the ground-water chemistry and microbial population downgradient from the wall.

Application of the automated ground-water monitoring system by the Cape Cod Toxics in Hydrology monitoring project was successful and demonstrated potential applications for the technology. The automated ground-water monitoring system began measuring field parameters before the zero-valent iron walls were installed, thereby recording background ground-water-quality properties and constituents. The system successfully recorded substantial changes in ground-water quality in a short time period (fig. 5) as the plume of reaction byproducts reached the monitoring well. Although the temperature record was relatively flat, evidence of the changes in ground-water chemistry caused by the injection of the zero-valent iron wall and the subsequent injection of the enzyme/pH adjustment compound are apparent in the other measurements. The complicated pattern of different measurements apparent in the different water-quality patterns presented in figure 5 reflects the complicated schedule for injection of the reactive wall slurry and the subsequent enzyme/pH adjustment compound. The pH record indicated an increase in pH, which correlates with increasing pH and alkalinities measured in the manual sampling program (Shannon Dionne, U.S. Geological Survey, oral commun., 1999). The specific-conductance record showed a primary arrival, a secondary arrival after a short plateau, and a peak in conductance as water and solutes from the wall injection and the enzyme/pH adjustment passed the measuring point. The DO record indicated that the ground water had become anoxic in response to emplacement of the reactive wall because DO decreased at the same time as the initial increase in specific conductance.

The automated monitoring system also was successful as a sentry well. On two separate dates the demonstration unit automatically notified the project chief through phone calls from a voice modem that specific conductance had exceeded 100 and then 200 µS/cm. These preestablished criteria were designed to facilitate the timing of manual sampling efforts to characterize the geochemical changes caused by the reaction byproducts when they initially appeared in the well. The triangles that are superimposed on the automated monitoring record in figure 5 indicate the dates of service visits and the comparability of automated and manual measurements made by using independent field probes.

Automated monitoring records collected by using accepted manual sampling protocols provide detailed information that is difficult to obtain, except with intensive and costly manual sampling programs. These detailed records present new opportunities for interpretation, and may also be helpful in determining or verifying hydrologic information for the study area. If available, a real-time record can be used to evaluate analytical results of periodic manual sampling efforts in the context of the variability in magnitude of changes in ground-water quality through time. For example, a quarterly manual sampling effort on the last day of July, October, and January would have missed both peaks in specific conductance that occurred between sampling rounds (fig. 5).

SUMMARY

Manual sampling and analysis of ground-water samples is labor- and resource-intensive. Process automation, although it will never completely replace manual methods, is an alternative because the real-time records can be used to optimize manual sampling efforts. Robowell is an automated process that was developed and tested by the USGS to provide a method for monitoring ground-water quality that meets the accepted manual-sampling protocols without incurring high labor and laboratory costs. This process is designed so that sampling equipment and instrumentation can be selected on the basis of the nature of the contaminants to be detected, site hydrogeology, and logistics such as available power and communications. The automated system can produce a detailed real-time data record with many more individual measurements than could be obtained by manual sampling methods, which are limited by cost and personnel constraints.

Six Robowell monitoring units have been in operation at one time or another since December 1994. These units have operated for more than 881 days with a loss of only about 3.4 percent of the period of record. The units have operated reliably to sample water under different hydrogeologic conditions, from different well designs, in different geochemical environments, and during all four seasons of the year. Performance was evaluated by a program of regular quality-control samples obtained by using independent water-quality probes, manual measurements, and laboratory analysis throughout the period of record. Results of this quality-control program verified the integrity of the automated sampling records and demonstrated that the automated monitoring system could accurately measure ground-water quality over a large range of geochemical conditions.

A Robowell prototype was installed at the MMR to monitor geochemical changes caused by emplacement of a zero-valent iron reactive wall. The automated ground-water monitoring system began measuring the field parameters before the zero-valent iron wall was installed, thereby recording background ground-water-quality properties and constituents. The monitoring unit recorded substantial changes in ground-water quality in a short period as the reaction by products of the wall and a subsequent enzyme/pH adjustment raised pH by almost a full unit, raised specific conductance by about 800 microsiemens per centimeter, and completely depleted the dissolved oxygen in ground water monitored in the well. The automated monitoring system also was successful as a sentry well by notifying the project chief using a voice modem that specific conductance had exceeded preset thresholds. If available, a real-time record can be used to evaluate analytical results of periodic manual sampling efforts in the context of the variability in magnitude of changes in ground-water quality through time.

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