Robowell: An automated process for monitoring ground water quality using established sampling protocols.

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Robowell: An Automated Process for Monitoring Ground Water Quality Using Established Sampling Protocols

By Gregory E. Granato and Kirk P. Smith

Abstract

Robowell is an automated process for monitoring selected ground water quality properties and constituents, by pumping a well or multilevel sampler. Robowell was developed and tested to provide a cost effective monitoring system that meets protocols expected for manual sampling. The process uses commercially available electronics, instrumentation, and hardware, so it can be configured to monitor ground water quality using the equipment, purge protocol, and monitoring well design that is most appropriate for the monitoring site and the contaminants of interest. A Robowell prototype was installed on a sewage-treatment plant infiltration bed that overlies a well-studied unconfined sand and gravel aquifer at the Massachusetts Military Reservation, Cape Cod, Massachusetts during a time when two distinct plumes of constituents were released. The prototype was operated from May 10 to November 13, 1996, and quality-assurance/quality-control measurements demonstrated that the data obtained by the automated method was equivalent to data obtained by manual sampling methods using the same sampling protocols. Water level, specific conductance, pH, water temperature, dissolved oxygen and dissolved ammonium were monitored by the prototype as the wells were purged according to U.S. Geological Survey ground water sampling protocols. Remote access to the data record, via phone modem communications, indicated the arrival of each plume over a few days and the subsequent geochemical reactions over the following weeks. Real-time availability of the monitoring record provided the information needed to initiate manual sampling efforts in response to changes in measured ground water quality that proved the method and characterized the screened portion of the plume in detail through time. The methods and the case study described are presented to document the process for future use.

Introduction

Manual sampling is a necessary component of ground water quality monitoring efforts, but it has technical and financial limitations. Most of the costs involved in operating a ground water monitoring network are for the labor and 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) identify the accuracy of the resulting estimates of the trends (Johnson et al. 1996; Zhou 1996). Process automation is an alternative to manual methods and automated methods have been used to monitor storm water, waste water, and ground water remediation installations. However, 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. Therefore, the USGS developed the process and the prototype described in this paper under a technology development program. The purposes of this paper are to describe the automated process for monitoring ground water quality properties and constituents using established sampling protocols, and demonstrate the utility of this process using a case study. Although the USGS automated ground water monitoring process can be adapted to follow most manual sampling protocols using commercially available equipment in a variety of sampling wells, this paper documents one case study using USGS manual sampling protocols and a particular set of equipment to introduce this automated ground water quality monitoring process.

The automated ground water monitoring process described here was conceived to determine maximum and minimum contaminant concentrations at a remote study site where many small, rapid, and discrete inputs of contaminated water would infiltrate to ground water from a surface water discharge pipe. The process was tested by manual and laboratory check measurements using a prototype installed at a USGS research site on Cape Cod, Massachusetts.

Automated systems have demonstrated great utility and cost savings by increasing the quantity and quality of data collected while decreasing labor and material costs (Jolley and Rivera 1989; Webster 1990; Chiron et al. 1995; Igarashi et al. 1995; Whitfield 1995; Church et al. 1996). Automated systems can increase data density because repeated measurements do not necessarily add costs. The increased data density enables identification of seasonal cycles, transient events, and noise in the data record (Whitfield 1995). Well-designed automated systems increase data reliability by incorporating feedback or alarm systems that can alert human operators to problems and/or select an alternative course of action to solve or bypass problems detected by system logic. Data from an automated system are stored electronically to facilitate their access and interpretation. For example, automated process-flow monitoring of production wells at dispersed or remote sites in the oil and gas industry has produced cost savings by reducing site visits for manual sampling, by increasing system efficiency using feedback and alarm systems, and by generating electronic production records (Amocams Systems Engineering 1989; Fink 1995).

Historically, passive monitoring devices have been used for automated ground water quality monitoring. These passive monitoring devices use a data logger to record measurements from a water-quality probe (or probes) suspended in a well to collect ambient data at a preset frequency. However, almost all scientific and regulatory assessments of ground water quality are based in-part upon the analysis of water samples withdrawn from a well. Thus, there are many questions about the comparability of the passive monitoring record obtained from an automatic-monitoring probe and the results from analysis of water samples obtained from a well.

The complex physical and chemical processes that affect the ground water quality monitored are unique to each monitoring well and vary with time. Studies of these processes raise questions about the validity of the water quality data obtained by passive monitoring probes. Experimental data indicates that the inorganic chemistry of water standing in a well for as little as 3 weeks can change measurably (Gillham et al. 1985). Temperatures, pH, oxidation reduction potentials, and total dissolved-solids concentrations of stagnant borehole water can differ from the water in the surrounding aquifer (Herzog et al. 1991). Rust and scale on well construction materials, bacterial activity in the well, and relatively rapid interactions with the atmosphere such as volatilization of volatile-organic compounds or effervescence of dissolved gases, will affect the quality of water that remains in the well for an extended period (Herzog et al. 1991). The quality of water measured in a well is dependent upon the physical and chemical heterogeneity in the interval of the aquifer screened by a well, flow and transport in the well, and possible skin effects at the well-aquifer interface (Reilly and LeBlanc 1998). Experimental data and modeling studies have demonstrated that ambient borehole flow can redistribute water and solutes within the well and the surrounding aquifer (Church and Granato 1996; Reilly et al. 1989). Information from periodic manual sampling events during a comparative test of active and passive automated monitoring methods indicates that passive measurements are substantially biased in relation to measurements made using standard manual sampling protocols, even in short-screen water-table monitoring wells (Smith and Granato 1998).

Since the ground water and aquifer materials surrounding each monitoring well have unique physical and chemical characteristics that can change with time, there will always be some debate about the proper sampling frequency, methods, and protocols appropriate for a given site. Consistant use of sampling equipment and purging protocols appropriate to a site are necessary to obtain consistent measurements that are representative of aquifer-water quality (Herzog et al. 1991; Koterba et al. 1995; Stone 1997). To obtain consistent and representative measurements, automated monitoring techniques should follow the same protocols selected for manual sample collection.

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 the protocols expected for manual sampling, and yet does not incur high labor and laboratory costs. 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 measured values. 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, (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 with measured values for the sampling interval before returning to the inactive

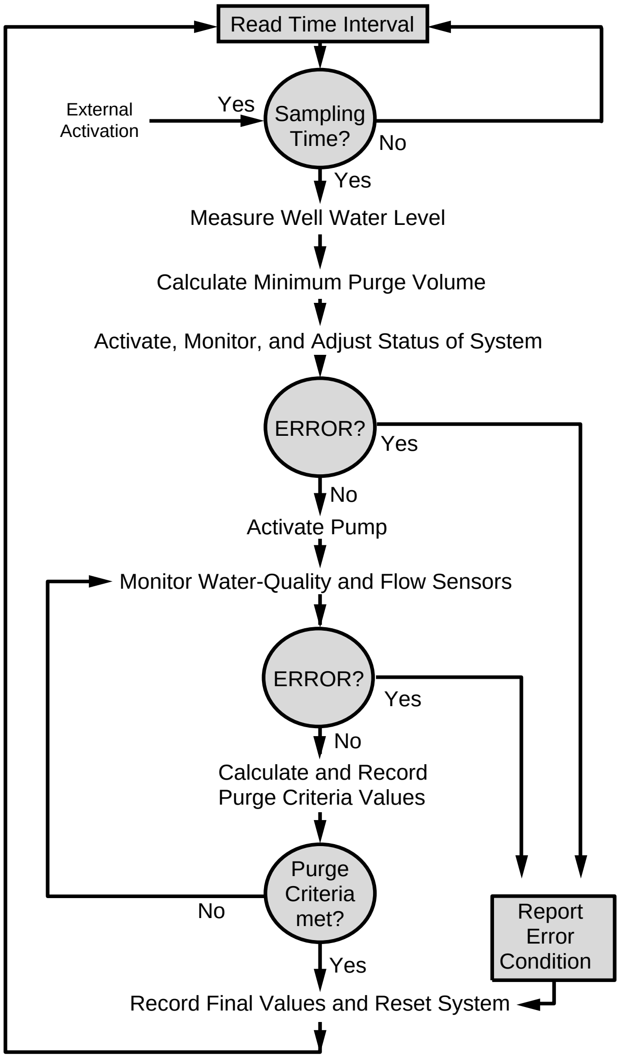

Figure 1. Generalized example of a process flow-chart for the automated ground water monitoring system.

mode. The system is controlled by a program that 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.

The Robowell process is better than existing automated ground water monitoring systems because it is designed to meet rigorous ground water sampling protocols. These protocols require monitoring and recording of properties and constituents in water pumped from a well or multilevel sampler until purge criteria have been met (Herzog et al. 1991; Koterba et al. 1995). Measured values of each water-quality property and constituent are recorded during the purge cycle to document that final recorded values may be considered representative of water in the aquifer. Therefore, measurements made by the Robowell process are directly comparable to measurements made during manual sampling events using the same protocols.

The Robowell process can identify changes in ground water quality on a real-time basis without the cost of sample collection, processing, and laboratory 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 from a ground water monitoring site may provide the context for the interpretation of periodic discrete samples collected for laboratory analysis. This record may be used with analysis of 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. Once the hydrologic and geochemical processes and time scales at a site are reasonably well assessed, the need for discrete samples for laboratory analysis can be substantially reduced without loss of critical information. Detection of substantial changes in measured values by remote query will 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 may 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 quality assurance/quality control (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 et al. 1991; Koterba et al. 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 sampling equipment and instrumentation can be selected on the basis of the nature of the contaminants to be detected, the hydrogeology of each 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.

Purge volume is a concern because of the potential purge-water disposal costs (Stone 1997). The methods chosen to dispose of purge water depend upon the purge criteria selected, the mission of the monitoring installation, the nature of the contaminants to be detected, the hydrogeology of each site, site logistics, and local regulations. Because the automated ground water monitoring process makes measurements, calculations, and decisions almost instantaneously, it will purge less water than a human operator following the same protocols. Also, this process has been designed with feedback loops to stop the purge and flag the data when the purge criteria have not been established within a

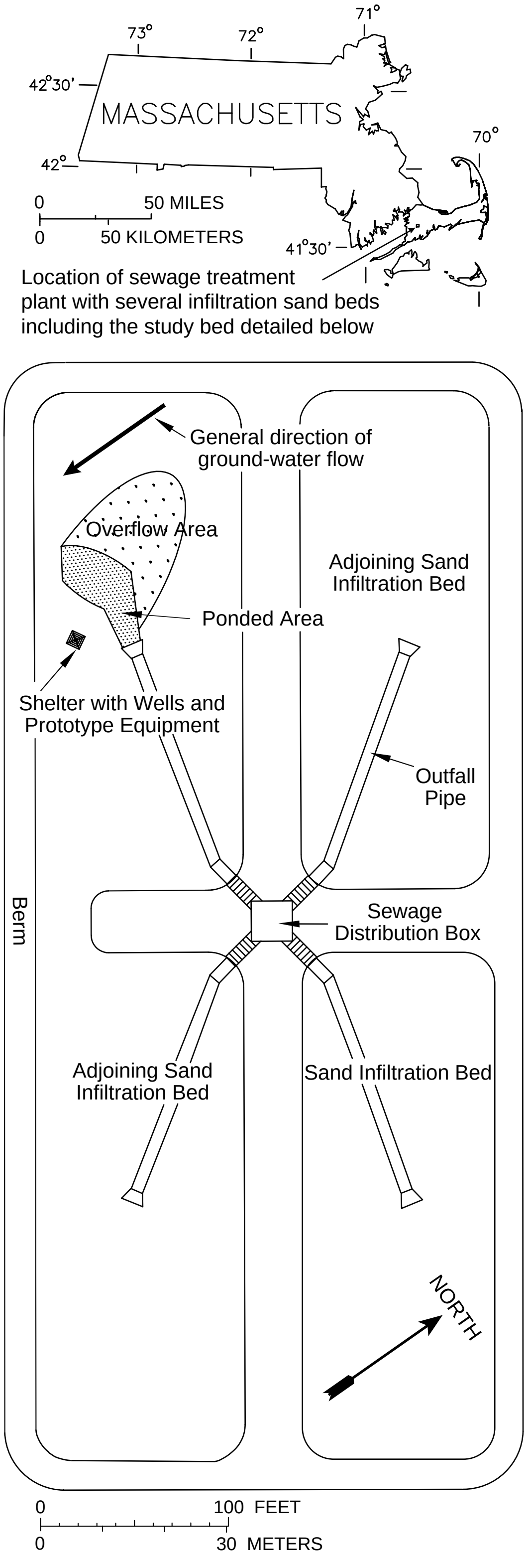

Figure 2. Map showing the study area and features of the study site, including the prototype equipment shelter, the impoundment, the overflow area, and features of the sand infiltration beds at the Massachusetts Military Reservation, Cape Cod, Massachusetts.

defined time period and/or within a defined purge volume. Primarily, the mission of the monitoring installation and nature of the contaminants to be detected establish the fate of the purge water. If the automated monitoring process is used as a sentry well to detect the arrival of a plume of contaminants, or if the contaminants being studied are not hazardous, then these relatively clean waters can be discharged to the land surface, or to a small leach field downgradient of the monitoring well. If the contaminants are hazardous, the purge water can be barreled for disposal. Also, a sentry well can be programmed to actuate a valve to divert purge water from local disposal to a collection barrel once contaminants are detected and to call a human operator once the barrel is near full capacity. If permissible, the purge volume can be reinjected back into the aquifer in a second well just downgradient of the monitoring well's capture zone using existing technology (Cardoso-Neto and Williams 1996). When local disposal of purge water is an option, the hydrogeology of each site is an important consideration. Also, the thickness of the unsaturated zone and the direction of ground water flow must be considered to prevent recycling of the purge water into subsequent measurement cycles. Purge water should be disposed in accordance with applicable regulations.

Case Study

A Robowell prototype was installed to test the technology at the U.S. Geological Survey Toxic Substances Hydrology Program Research Site (LeBlanc et al. 1991) in a sand infiltration bed of a sewage-treatment plant on the Massachusetts Military Reservation, Cape Cod, Massachusetts (Figure 2). The wells for the prototype were drilled at a study site on a sand infiltration bed used for the disposal of effluent from a sewage-treatment plant in the process of being decommissioned. Two events causing geochemical changes would occur during the study period as a result of the decommissioning of the sewage plant: (1) a large pulse (about 8.7 million liters) of partially treated sewage effluent would be applied to the infiltration bed; and (2) the solids remaining in the treatment tanks would be limed and pressed, producing another large pulse (about 5.3 million liters) that would be applied to the infiltration bed, producing two distinctive plumes of sewage effluent in ground water.

The prototype system was tested at this research site for several reasons. The expected changes in ground water quality caused by the two pulses of the effluent and subsequent cessation of effluent application would provide specific events to be monitored over a wide range of geochemical conditions. The unconsolidated deposits of sand and gravel in the area form a permeable, unconfined (water table) aquifer that is favorable for a short-term ground water quality investigation, because the hydrologic and chemical characteristics of this aquifer are well studied and well defined (LeBlanc et al. 1991).

Description of Site and Equipment

Two test wells and an equipment shelter housing the electronics, instrumentation, equipment, and hardware

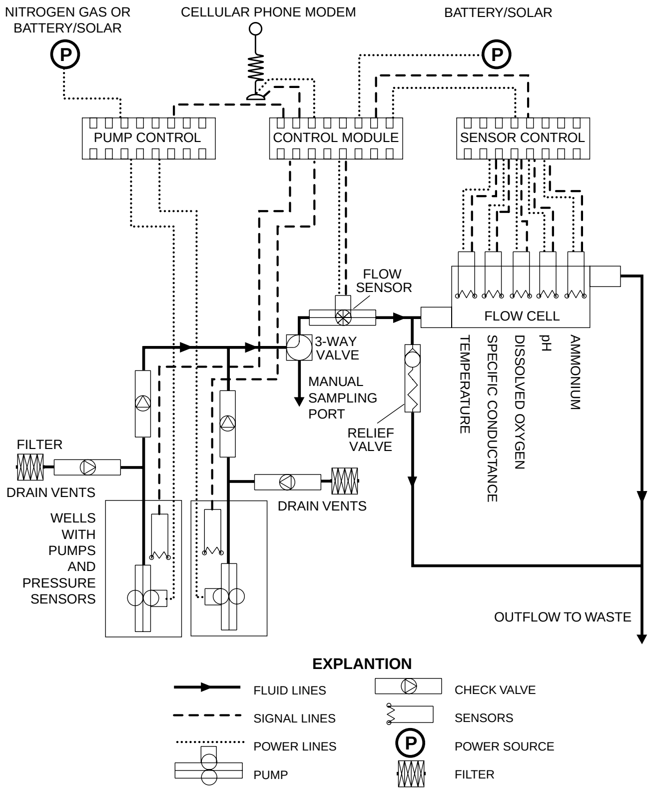

Figure 3. Schematic diagram of the prototype system showing the flow train and equipment used at the test site.

for the prototype were emplaced in a sand infiltration bed about 6 m downgradient of an impoundment constructed to form a line source of ponded infiltrating-water for the study (Figure 2). A semi-elliptical overflow area in the bed behind the impoundment was flooded when flow rates from the discharge pipe exceeded the infiltration capacity of soils in the impoundment. Two 5-cm diameter polyvinyl-chloride wells were emplaced, one screened from about 1.5 m above to 1.5 m below the water table (about 7.3 m below land surface) and another screened from about 1.5 m to 3 m below the water table (USGS wells SDW 479-0028 and SDW 479-0033, respectively).

The system schematic (Figure 3) indicates the flow train and equipment used in this prototype. The system utilized a Campbell Scientific Incorporated (CSI) CR10 data logger as the control module for the process and a CSI SM192 solid-state storage device to store data. Because electric and phone services were not readily available, batteries recharged by solar panels were used to power the controllers and other instruments, nitrogen gas was used to power the QED bladder pumps through a pneumatic logic controller, and a CSI DC112 telephone modem was used for communications. The water level in the water-table well was monitored with a Keller pressure transducer (operating range of 0-0.176 kg per square cm). A hand-operated Plastomatic three-way valve was placed near the beginning of the flow train to divert water for manual collection of samples. A 1.27 cm Data Industrial flow sensor was 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, was used as a control module for the water temperature, pH, specific conductance, dissolved oxygen, and dissolved ammonium probes under data logger control. Other instruments not shown in Figure 3 were used to monitor nitrogen pressure, shelter air temperature, battery voltage, and other system parameters.

Purge Criteria

Several purge criteria were used while developing the prototype. The first purge criterion simply required evacuation of at least three borehole volumes of water (theoretically, to remove stagnant borehole water and to sample water representative of the aquifer in the screened zone). The system monitored and recorded water level, water temperature, pH, specific conductance, and dissolved oxygen to check the assumption that geochemical stability had been achieved after three borehole volumes had been pumped. The second purge criterion required physicochemical stability (theoretically, to indicate that the sample water was representative of the aquifer in the screened zone). Water temperature, pH, specific conductance, and dissolved oxygen were measured and recorded until the variance of the last 5 readings for each property and constituent was within a predetermined range (0.2 degrees C for temperature, 0.1 units for pH, 3 percent for specific conductance, and 0.3 mg/L for dissolved oxygen) around the average of the last 5 recorded values. The third purge criterion followed the ground water sampling protocol developed for the USGS National Water-Quality Assessment Program which was also based upon the assumption that geochemical stability would indicate representative sampling from the aquifer in the screened zone (Koterba et al. 1995). Before the pump was activated, the system measured the water level and calculated the volume of water standing in the well using the inside diameter of the well. The flowmeter monitored the pumping rate during purging and sampling. Water temperature, pH, specific conductance, dissolved oxygen, and ammonium were measured and recorded every 3 minutes during the purge. The well was considered purged when the values of 5 successive measurements of these properties and constituents fell within the previously specified ranges for physicochemical stability around the median of the last 5 recorded values (Figure 4). As specified by the protocol (Koterba et al. 1995), the final measurement of pH and the median of the last five measurements of each of the other properties and constituents were recorded as the final value.

Measurement and Recording Frequency

Measurements of water-quality properties were made at different time intervals on the basis of expected changes in ground water quality. Typically, a daily time interval was used except during times of abrupt water-quality changes, when measurements were taken every 12 hours. Recorded data were either downloaded from the control and recording device in the field with a laptop computer or retrieved remotely by use of the cellular

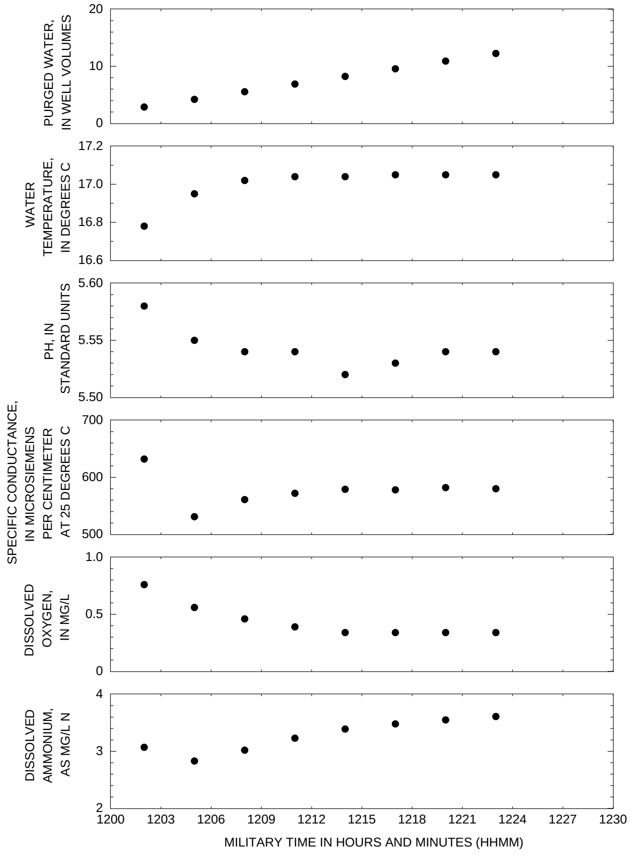

Figure 4. Real-time purge data collected on October 6, 1996 by the automated ground water monitoring process at well SDW 479-0028, Cape Cod, Massachusetts.

telephone modem. The prototype operated successfully from May 10 to November 13, 1996, and sufficient data were collected to demonstrate that the data obtained by the automated method were equivalent to dataa obtained by manual sampling methods using the same protocols (Figure 5).

Quality Assurance/Quality-Control Program

The quality-assurance/quality-control program was based on periodic comparative measurements using instrument calibration readings and measurements by independent field probes, as well as manual sampling to make field measurements and collect duplicate and equipment-blank samples for analysis at the USGS National Water Quality Laboratory (NWQL). Calibration and comparative measurements, taken while the system was manually controlled after determining post-purge stability, were used to assess system performance about every 2 weeks. Comparative water-quality measurements were made in an overflowing aspirated bottle connected to the three-way valve in the main flow line. Comparative water temperature measurements were recorded using a hand-held alcohol thermometer certified by the National Institute of Science and Technology (NIST). Comparative specific conductance and pH measurements were made using laboratory-calibrated field meters (Orion 290A and Orion 124), and in water samples sent to the NWQL. Dissolved-oxygen measurements greater than 0.9 mg/L were determined by Winkler titrations, and measurements of dissolved oxygen less than 0.9 mg/L were determined by a CHEMetrics kit (K-7501). During the study period, the pH remained less than 9, therefore almost all ammonia in solution would be present as ammonium ions (Hem 1992). Measurements of dissolved ammonia/ammonium as nitrogen determined by a CHEMetrics kit (K-1510) and by the NWQL do not differentiate between species. Samples for analysis of dissolved ammonia as nitrogen, and other nitrogen species also were collected and sent to the NWQL about every 2 weeks as duplicates to verify field measurements and to quantify nitrogen speciation. Equipment blanks--samples of deionized water processed through all pumps and wetted parts of the system--were analyzed at the NWQL for concentrations of major ions and nutrients. These blanks were collected prior to installation of the monitoring system to ensure that the sampling system would not measurably change properties and constituents of ground water. Recalibration of water-quality system probes and routine maintenance was performed at frequencies suggested by the probe manufacturers. Also, data were regularly retrieved through remote communications and examined for changes or trends in water-quality measurements. Changes or trends in water-quality measurements prompted a field visit to substantiate the changes with independent manual measurements and/or to recalibrate and maintain the water-quality probes.

Comparison of Automated and Manual Measurements

Automated water-quality measurements and manual field and laboratory measurements measured in the water-table well (SDW 479-0028) correlated closely for all properties and constituents (Figure 5). Automated measurements of pH were slightly but consistently lower than laboratory and field check measurements. The small bias in automated pH measurements were caused by pressurization of the membrane in the pH probe by the elevated water pressure in the flow cell. Close correlation between automated and manual measurements was facilitated by the remote communication capability through the modem. System measurements could be examined at any time from the office via the modem, and any unexpected changes in water quality prompted a site visit for manual calibration and testing. For example, a field visit confirmed that the ammonium probe had failed when the automated system indicated substantial increases in ammonium concentrations in mid-July. The probe was replaced and the period during which the probe was malfunctioning was shown as one of "no record" (Figure 5).

The automated monitoring system successfully documented the rapid and short-term changes in hydrologic and geochemical conditions resulting from the discharge of the sewage-plant effluent. The large discharge events and normal to high monthly precipitation totals were not notable in measured water levels because of the high hydraulic conductivities of the aquifer (Reilly and LeBlanc (1998), report values of horizontal

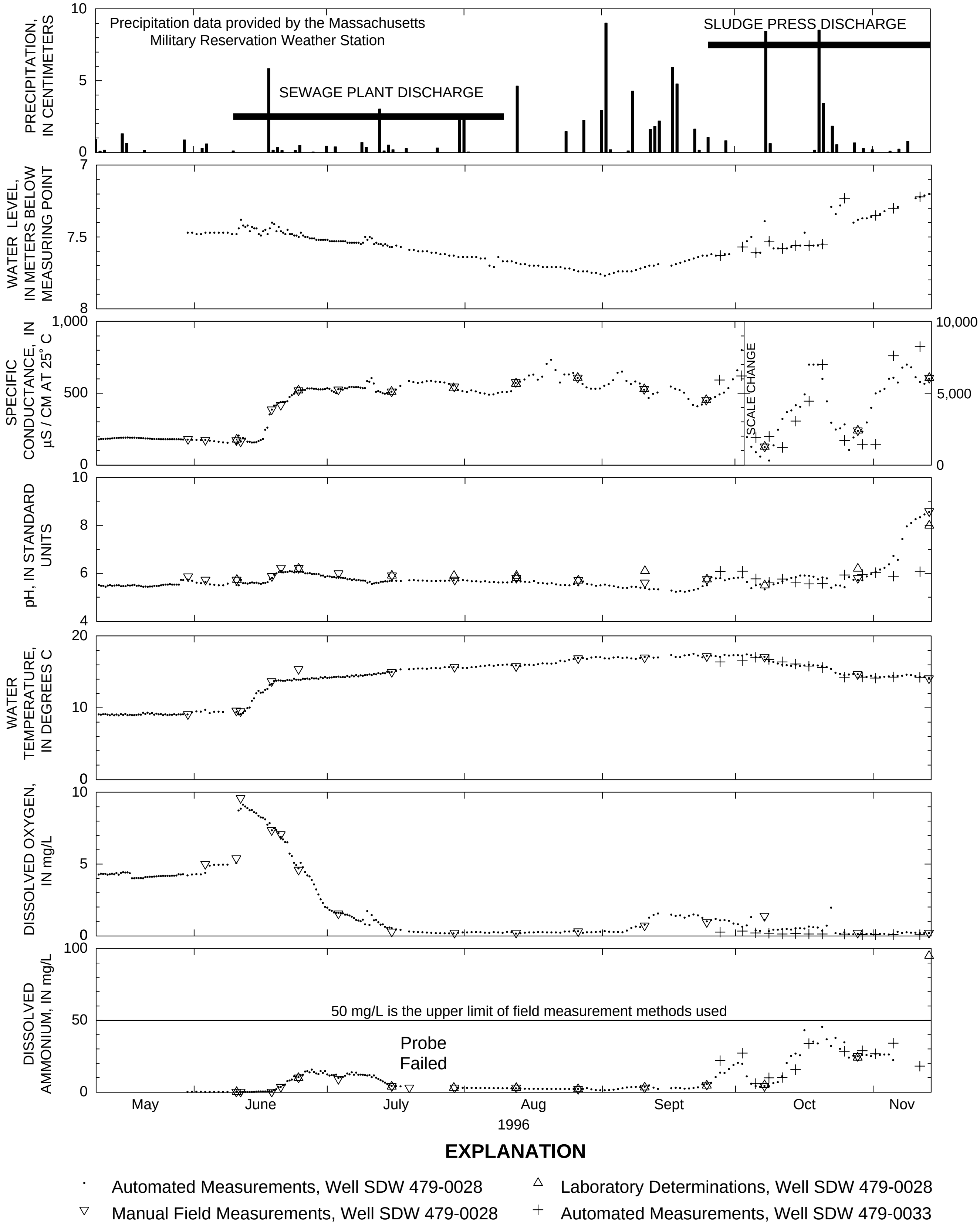

Figure 5. Automated and manual measurements of ground water quality from wells SDW 479-0028 and SDW 479-0033, Cape Cod, Massachusetts.

hydraulic conductivity that range from 24 to 295 meters per day in the same aquifer near the study site). However, the effect of sewage discharge on ground water quality properties and constituents measured by the automated system aand confirmed by manual check measurements and laboratory analysis of samples from the water table well (SDW 479-0028) was relatively rapid (about 5-6 days for specific conductance, about 8-10 days for pH and ammonium, about 3 days for water temperature, and about 1 day for dissolved oxygen). Automated measurements of water-quality properties and constituents in the adjacent well (SDW479-0033), which screened the next 1.5 m interval below the water table well, showed similar variations (Figure 5) and demonstrated the ability of the system to monitor more than one well or multilevel sampling port in the same vicinity.

Summary

The Robowell process can identify changes in ground water quality on a real-time basis by providing data comparable to manual measurements on a frequent basis without the cost of sample collection, processing and analysis. Robowell is an automated process for monitoring and recording values of selected ground water-quality properties and constituents by pumping a well or multilevel sampler using preselected purge criteria that would meet protocols expected for manual sampling. The Robowell process can be used to sample different monitoring wells and to follow different purge protocols. The methods and the case study described are presented to document the process for future use. Automated systems have demonstrated great utility and cost savings by increasing the quantity and quality of data collected while reducing sampling costs.

The Robowell prototype was installed on a sewage-effluent infiltration bed in a well studied unconfined sand and gravel aquifer on the Massachusetts Military Reservation, Cape Cod, Massachusetts. The prototype utilized purge criteria recommended in ground water sampling protocols developed for the USGS National Water-Quality Assessment Program. Water temperature, pH, specific conductance, dissolved oxygen, and ammonium were recorded every 3 minutes during the purge. The well was considered purged when the values of five successive measurements of the preselected properties and constituents fell within specified ranges for physicochemical stability around the median value. The prototype operated successfully from May 10 to November 13, 1996, during which two large pulses of treated sewage effluent were discharged to the aquifer. Quality-assurance/quality-control data obtained during operation of the prototype demonstrated that the data obtained by the automated method was equivalent to data obtained by manual sampling methods using the same protocols. Once such a system is put in practice, substantial changes or trends in measured water-quality properties and constituents could be used to prompt manual measurements to verify these changes or trends in water quality.

The U.S. Geological Survey has submitted a patent application for the automated ground water monitoring system and method. For more information about this and other available technologies please contact the U.S. Geological Survey Technology Enterprise Office.

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Biographical Sketches

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The automated ground water monitoring project web page is available on the internet at:

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