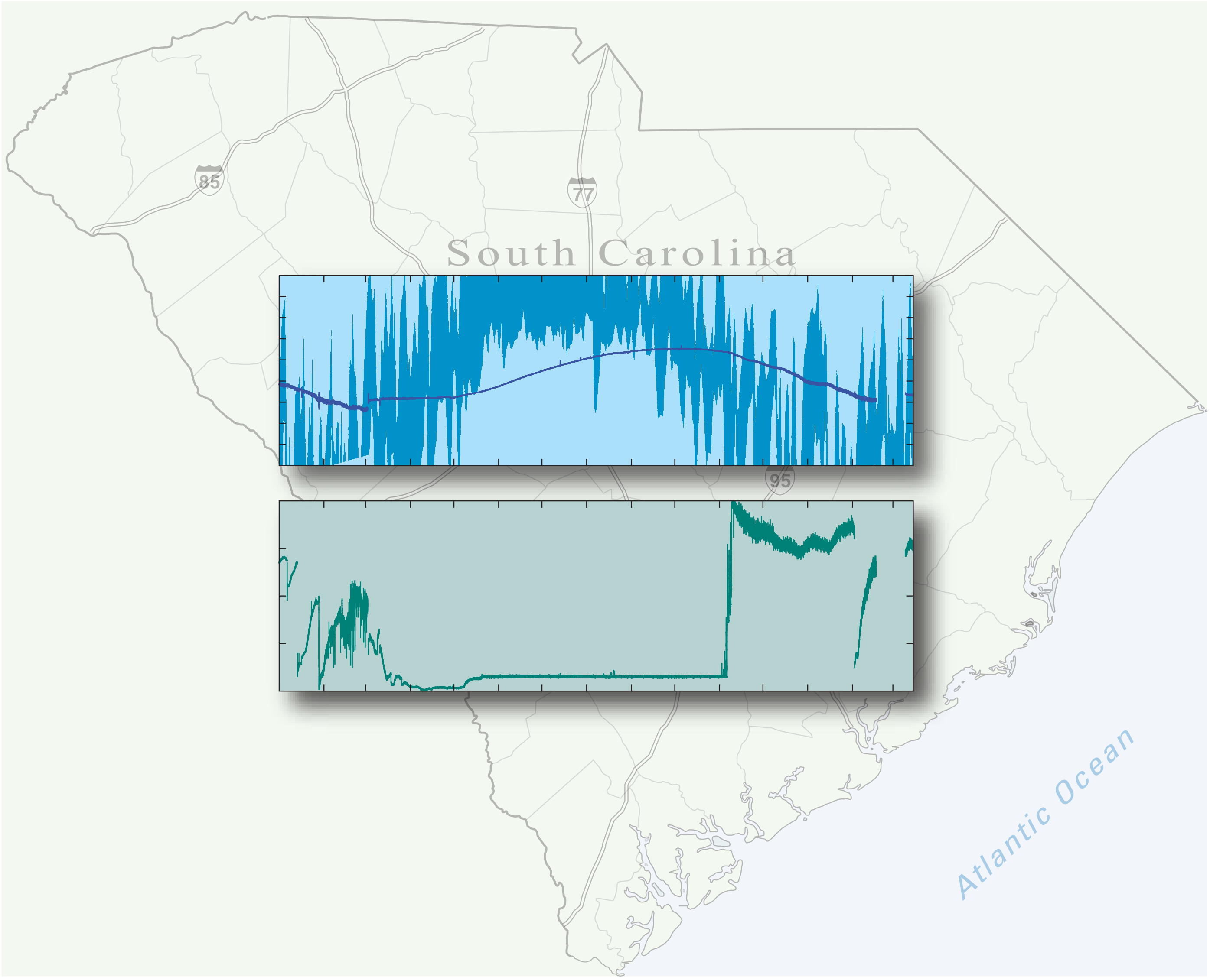
science for a changing world

Prepared in cooperation with the
Naval Facilities Engineering Command Southeast

Influence of In-Well Convection on Well Sampling



Scientific Investigations Report 2006–5247

U.S. Department of the Interior
U.S. Geological Survey

Cover illustration based on figure 5, p. 5.

Influence of In-Well Convection on Well Sampling

By Don A. Vroblesky, Clifton C. Casey, and Mark A. Lowery

Prepared in cooperation with the
Naval Facilities Engineering Command Southeast

Scientific Investigations Report 2006–5247

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark Myers, Director

U.S. Geological Survey, Reston, Virginia: 2006

For product and ordering information:
World Wide Web: *http://www.usgs.gov/pubprod*
Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: *http://www.usgs.gov*
Telephone: 1-888-ASK-USGS

Suggested citation:
Vroblesky, D.A., Casey, C.C., and Lowery, M.A., 2006, Influence of in-well convection on well sampling:
U.S. Geological Survey Scientific Investigations Report 2006–5247, 13 p.

Contents

Figures

Figures—continued

Table

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
foot per year (ft/yr)	0.3048	meter per year (m/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

Abbreviations

1,1-DCA	1,1-dichloroethane
1,1-DCE	1,1-dichloroethene
1,1,1-TCA	1,1,1-trichloroethane
bls	below land surface
cDCE	*cis*-1,2-dichloroethene
CVOCs	chlorinated volatile organic compounds
DO	dissolved oxygen
Fe^{2+}	dissolved ferrous iron
mg/L	milligrams per liter
mL/min	milliliter per minute
µg/L	micrograms per liter
NAVFAC SE	Naval Facilities Engineering Command Southeast
NWS	Naval Weapons Station
PCE	tetrachloroethene
PDBS	passive diffusion bag sample
ppb	parts per billion
PRB	permeable reactive barrier
SWMU	Solid Waste Management Unit
TCE	trichloroethene
TEAP	terminal electron accepting process
USGS	U.S. Geological Survey
VC	vinyl chloride
VOC	volatile organic compound

Influence of In-Well Convection on Well Sampling

By Don A. Vroblesky, Clifton C. Casey[1], and Mark A. Lowery

Abstract

Convective transport of dissolved oxygen (DO) from shallow to deeper parts of wells was observed as the shallow water in wells in South Carolina became cooler than the deeper water in the wells due to seasonal changes. Wells having a relatively small depth to water were more susceptible to thermally induced convection than wells where the depth to water was greater because the shallower water levels were more influenced by air temperature. The potential for convective transport of DO to maintain oxygenated conditions in a well was diminished as ground-water exchange through the well screen increased and as oxygen demand increased. Convective flow did not transport oxygen to the screened interval when the screened interval was deeper than the range of the convective cell.

The convective movement of water in wells has potential implications for passive, or no-purge, and low-flow sampling approaches. Transport of DO to the screened interval can adversely affect the ability of passive samplers to produce accurate concentrations of oxygen-sensitive solutes, such as iron. Other potential consequences include mixing the screened-interval water with casing water and potentially allowing volatilization loss at the water surface. A field test of diffusion samplers in a convecting well during the winter, however, showed good agreement of chlorinated solvent concentrations with pumped samples, indicating that there was no negative impact of the convection on the utility of the samplers to collect volatile organic compound concentrations in that well. In the cases of low-flow sampling, convective circulation can cause the pumped sample to be a mixture of casing water and aquifer water. This can substantially increase the equilibration time of oxygen as an indicator parameter and can give false indications of the redox state.

Data from this investigation show that simple in-well devices can effectively mitigate convective transport of oxygen. The devices can range from inflatable packers to simple baffle systems.

Introduction

Water within wells can develop convective circulation as a result of as little as 0.03 degrees Celsius (°C) increase in water temperature per 3.28 feet (ft) (1 meter) of depth (Diment, 1967; Gretener, 1967; Sammel, 1968) in a 2-inch (in.) well. A thermally unstable condition is defined, for the purposes of this investigation, as an increase in water temperature with depth, such that convection is initiated. In some cases, the unstable temperature distributions resulting from temperatures dropping below the annual average temperature can propagate to depths of 65 ft or more (Salem and others, 2004; Ferguson and others, 2003). During summer months, warm water overlying cooler water can result in a zone of non-convecting water at the top of the water column (considered thermally stable in this report), while convective flow continues in deeper parts of the well bore (Martin-Hayden, 2001; Martin-Hayden and Britt, 2006). Early investigations found that the critical temperature gradient initiating convective flow was affected by a variety of factors, including the properties of the fluid and the size of the well (Hales, 1937; Diment, 1967). Increasing well diameter from 2 to 6 in. substantially decreases the critical gradient required to initiate convection (Sammel, 1968). As salinity increases, the critical gradient required to initiate convection decreases at temperatures between 5°C and 20°C (Sammel, 1968).

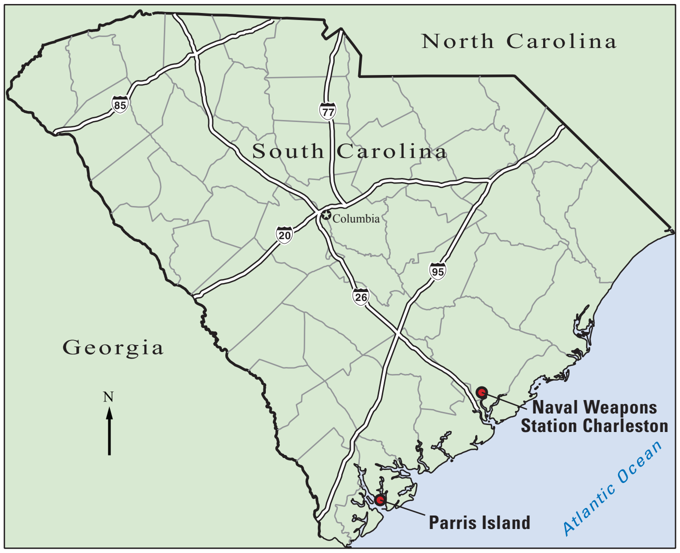
Such convection was not traditionally considered to be problematic to sampling monitoring wells because sampling typically involved great disruption to the water column in the well. With the advent of low-flow and no-purge sampling, however, convective flow within the well has the potential to increase project costs by substantially increasing sampling time when collecting low-flow samples and to affect the representativeness of both low-flow and passive approaches for ground-water sampling. Tests done under controlled laboratory conditions (Martin-Hayden, 2000) showed that during low-flow sampling, an increase of more than 0.2°C per 3.28 ft can induce convective flow in a well bore sufficient

---

[1] Naval Facilities Engineering Command Southeast

to overcome pump-induced velocities (i.e. 200 milliliters per minute [mL/min]) and mix casing water with aquifer water at the pump. The tests found that a slight density difference of 0.005 percent allowed 5 percent of the casing water to mix with the aquifer water as a result of thermal convection even after eight casing volumes had been removed. Based on these findings and on the results of testing in a closed borehole, the authors hypothesized that convective cells within wells could transport oxygen and other solutes to the screened intervals of monitoring wells, potentially altering the water chemistry of samples collected from the well (Martin-Hayden, 2000, 2001; Martin-Hayden and Britt, 2006). To mitigate this problem, Martin-Hayden (2000) recommended purging three to five casing volumes prior to sampling where thermal convection was suspected.

The purpose of this report is to present the findings of a field investigation to (1) determine whether oxygen convection to monitoring well screens in anaerobic aquifers takes place under field conditions, (2) examine some of the factors influencing such convection, and (3) test the use of simple baffles as a tool to mitigate such convection. The investigation was a cooperative effort between the U.S. Geological Survey (USGS) and the Naval Facilities Engineering Command Southeast (NavFac SE). Data from three sites in South Carolina were used in this investigation (fig. 1). The sites in South Carolina are Solid Waste Management Unit (SWMU) 12 and SWMU17 at the Naval Weapons Station (NWS) Charleston, in North Charleston, and SWMU45 at the Marine Corps Recruit Depot Parris Island, in Beaufort. The predominant groundwater contaminants at all sites were chlorinated solvents.



Base from U.S. Geological Survey digital line graphs, 1:2,000,000, Albers projection, Standard parallels 29°30′N and 45°30′N, central meridian 96°00′W

Figure 1. Locations of study areas in South Carolina.

Methodology

Temperature in wells was obtained by using a variety of methods. The methods included long-term deployment of Thermocron iButtons, YSI XLM multisensors, and Solinst LTDO oxygen and temperature sensors. Vertical profiling in monitoring wells was done either by examining stabilized iButtons, or by incrementally lowering a YSI 600 XLM or LTDO sensor and allowing it to stabilize between readings. The Thermochron iButton is a temperature-logging disk approximately 0.1 in. in diameter and 0.04 in. thick. The loggers have an accuracy of ±0.05°C and a precision of ±0.4°C (Johnson and others, 2005). The iButtons were heat-sealed in polyethylene prior to deployment in wells; however, Johnson and others (2005) suggested that sealing these tools is not necessary when used to depths of up to 16.4 ft. The iButtons typically were deployed at multiple depths in open wells or in wells with flow-limiting baffles. All wells examined in this investigation were constructed of 2-in.-diameter poly vinyl chloride (PVC).

The YSI 600 XLM multi-parameter sensor used in this investigation provides logging of temperature, conductivity, dissolved oxygen (DO), pH, and depth. The DO resolution is 0.01 milligram per liter (mg/L) with an accuracy of ±0.2 mg/L between 0 and 20 mg/L. The YSI and Solinst sensors were used to simultaneously measure oxygen and temperature and to record the data during long-term deployment.

Wells were sampled by using low-flow methods (Barcelona and others, 1994; Shanklin and others, 1995; Sevee and others, 2000). During low-flow sampling, the wells were purged at a rate of approximately 100–200 mL/min, until the temperature, pH, DO, and specific conductance stabilized and no additional water-level drawdowns were observed. Stabilization of temperature, pH, DO, and specific conductance were verified by passing the water through a flow-through cell containing sensors. The pumping was considered to be stabilized when the observed changes over three 3-minute intervals were within ±3 percent for temperature and specific conductance, within ±0.1 unit for pH, and within ±10 percent for DO.

Two types of flow-limiting baffles were tested in wells during this investigation. One type consisted of an inflated packer approximately 6 in. long (ProHydro, Inc., New York). The packer was constructed of Teflon endpieces and a rubber inflatable diaphragm. Nitrogen was used to inflate the packer in the borehole immediately above the well screen. The second type of baffle consisted of a series of high-density polyethylene disks cut slightly larger than the well diameter and mounted on a threaded steel rod with plastic disks on the ends of the rod to keep it vertical (fig. 2). Whereas the construction materials of the baffles used in this investigation may not be suitable for all contaminated aquifer applications, these prototypes were used to demonstrate the potential for flow-limiting baffles to mitigate the negative effects of in-well circulation. The baffles were installed approximately 1 ft above the well screens. DO was monitored beneath the packer by using a Solinst LTDO DO sensor.

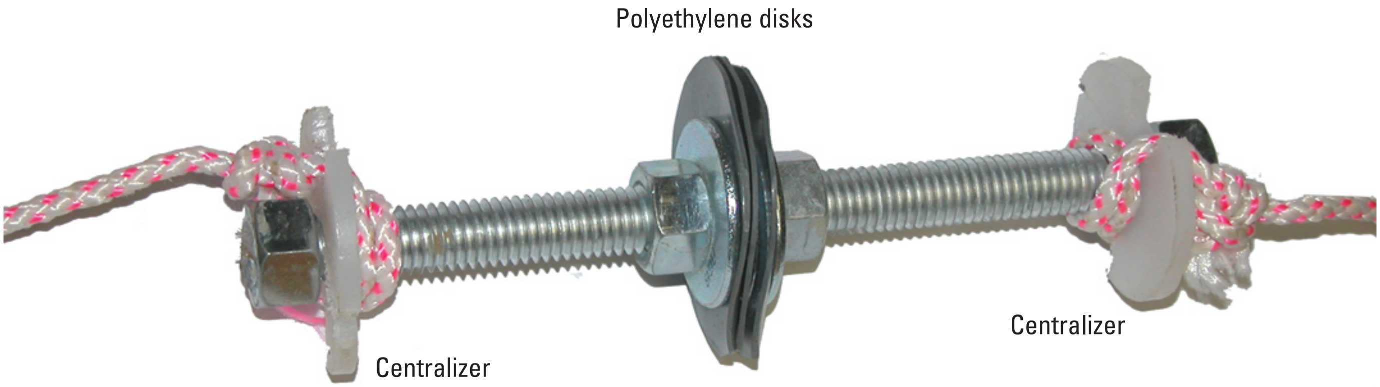


Figure 2. Simple baffle placed approximately 1 foot above the well screen in well 12MW-29S, Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina.

As a test to determine whether a simple baffle constructed of polyethylene disks was effective, the baffle was deployed in well 12MW-29S at SWMU12, NWS Charleston, and the well water was modified to produce thermally convective transport of DO. The test on April 18, 2006, consisted of pumping the well from the top of the water column until approximately two to three casing volumes of water had been removed so that water in the well was composed entirely of anaerobic aquifer water. A test of the discharging water using a CHEMets colorimetric method showed the DO concentration in the discharging ground water to be 0.2 mg/L. Following purging, temperature and oxygen sensors and a baffle were deployed down the well (table 1). The top 1.5 ft of the water column was then aerated by pumping air through an air stone. Deionized ice then was dropped into the well to chill the upper part of the water column and initiate convective flow. A similar test in the same well was conducted the previous week (April 11, 2006), but without the baffle, as a comparison.

Table 1. Depths of water surface, sensors, baffle, screened interval, and bottom of well during a field test of the in-well baffle at well 12MW-29S, Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina, April 18, 2006.

Device deployed	Feet below land surface
Water surface	3.39
Temperature sensor	4
Temperature sensor	5.5
Temperature/oxygen sensor	6.4
Temperature sensor	7.8
Baffle	8.25
Temperature sensor	8.8
Top of well screen	9.75
Temperature/oxygen sensor	10.8
Bottom of well	12

Influence of In-Well Convection on Well Sampling

The water-temperature distribution in well MW-04D at Parris Island shows that during June through September, the shallowest water was the warmest in the well bore (fig. 3*A*). When relatively warm water overlies cooler water, thermal convection is inhibited (thermally stable). By late August, the zone of thermal stability extended to a depth of about 20 ft, with thermally unstable water below that depth.

Beginning in about November, thermal instability developed in the shallow part of the well as the shallow water became cooler than the water beneath it (figs. 3*A*, *B*). In November 2005, the thermally unstable zone extended down to a depth of about 16 ft. At greater depths, warm water was over cooler water, resulting in thermally stable conditions with no tendency for convective flow (fig. 3*B*). By late December, the zone of thermal instability extended to a depth of about 23 ft (fig. 3*B*). Thus, the zones of thermal stability and instability shifted vertically as the seasons progressed. This finding is consistent with Martin-Hayden's (2001) theoretical prediction based on equations of Sammel (1968).

The implications of thermal instability in well bores can be seen in the distribution of DO in well 12MW-13S (NWS Charleston). Low-flow sampling results from about 6 years of sampling well 12MW-13S showed that DO concentrations typically were 0.3 mg/L or less, and sometimes were less than 0.025 mg/L. Exceptions were during winter sampling, when DO concentrations after stabilization of indicator parameters following low-flow purging were about 1.5 mg/L (February 2002, January 2003). Because the aquifer in which this well is screened is separated from land surface by about 10 ft of dense clay, it seemed unlikely that the aquifer became aerobic during the winter as a result of local recharge. Examination of temperature and DO data, however, indicated that the source of the DO is convective in-well flow. During June at well 12MW-13S, when warmer water overlaid cooler water (fig. 4*A*), the thermal stability prevented convective in-well

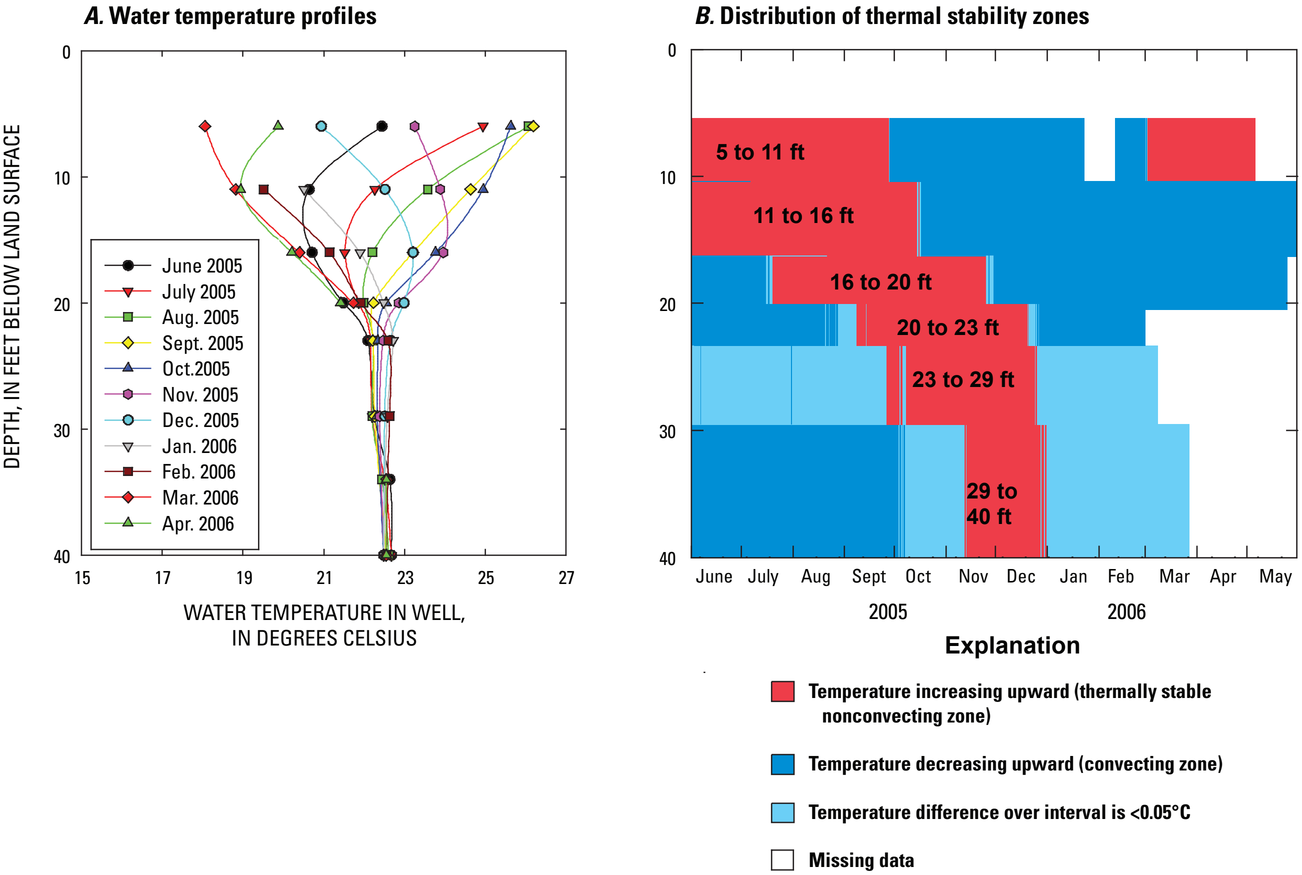


Figure 3. Water-temperature profiles and distribution of thermal stability zones in well MW-04D, Solid Waste Management Unit 45, Marine Corps Recruit Depot Parris Island, Beaufort, South Carolina, 2004–2005.

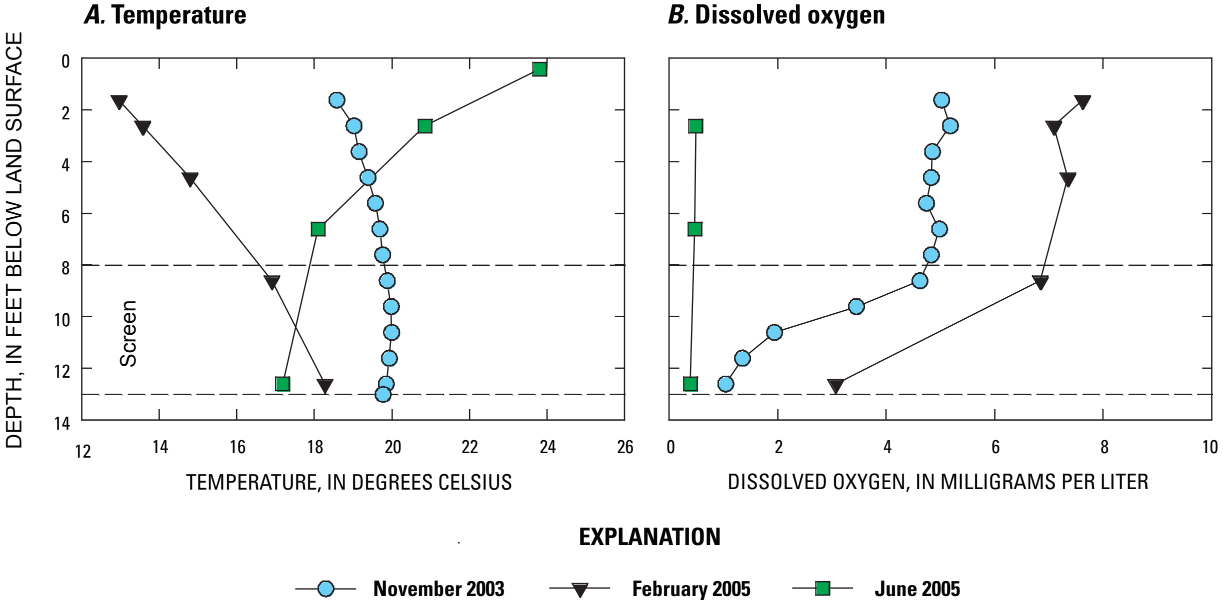


Figure 4. Temperature and dissolved oxygen variation with depth at well 12MW-13S, Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina, 2003–2005.

flow, and the DO in the well water at the screened interval reflected anaerobic aquifer conditions (fig. 4*B*). In February 2005, when cooler water overlaid warm water (fig. 4*A*), convection cells transported DO to the screened interval (fig. 4*B*). In the transitional month of November 2003, the thermal gradient was substantially smaller than in February 2005. In November 2003, the shallow part of the well consisted of cool water overlying slightly warmer water, allowing convective flow of water and DO. At a depth of about 11 to 13 ft, however, the thermal gradient showed a slight cooling with depth (fig. 4*A*). The deeper part of the screened interval was thermally stable, and the DO concentration was relatively low. Thus, in this shallow well, DO was transported to the screened interval during the winter by in-well convection.

The timing of the oxygen transport to the screened interval can be seen in figure 5. In 2004, as the daily air temperature range fell below the ground-water temperature, convection cells developed that transported DO to the sensor in the screened interval, 12 ft below land surface (about 10 to 11 ft below the water surface) (figs. 5*A* and 5*B*). During a sampling event on February 2, 2005, the well was purged from the top of the water column to attain anaerobic conditions in the well. By 3 days later, the DO concentration in the well-casing water at the screen had risen to greater than 3 mg/L and continued to rise over the next several days, attesting to the ability of convective movement to rapidly turn over well water (fig. 5*B*). In this well, thermal stability appears to be reestablished by about late March, allowing DO levels in the screened interval to be controlled by aquifer DO concentrations.

Figure 6*A* shows a comparison of the temperature gradients in wells on February 1, 2005, at SWMU12. The shallowest water temperature measurement in each well shows an approximate correspondence with the depth to water, at least to a depth of about 4.5 ft. The upper part of the water column was coldest in wells where the depth to water was smallest and most readily influenced by air temperature. The colder water results in a greater density and a more vigorous convection than found in wells with warmer water. In wells where the temperature gradient is relatively large, there is a greater amount of convective transport than in other wells. As shown in figure 6*B*, convection transports varying amounts of DO to varying depths in the wells. Thus, depth to the water in the well is one factor influencing in-well transport of DO, with shallower depths to water being most influenced by air temperature.

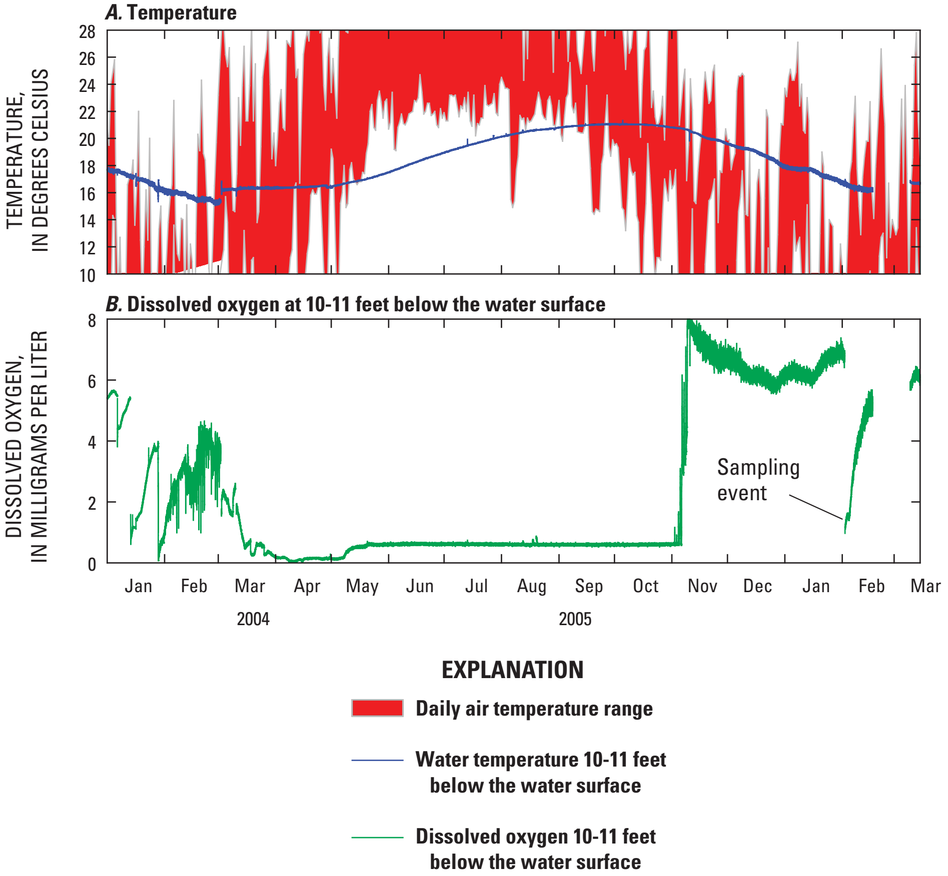


Figure 5. (*A*) Changes in air temperature and water temperature at a depth of 12 feet below land surface (about 10 to 11 feet below the water surface) and (*B*) changes in dissolved-oxygen content in well 12MW-13S, Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina, 2004–2005.

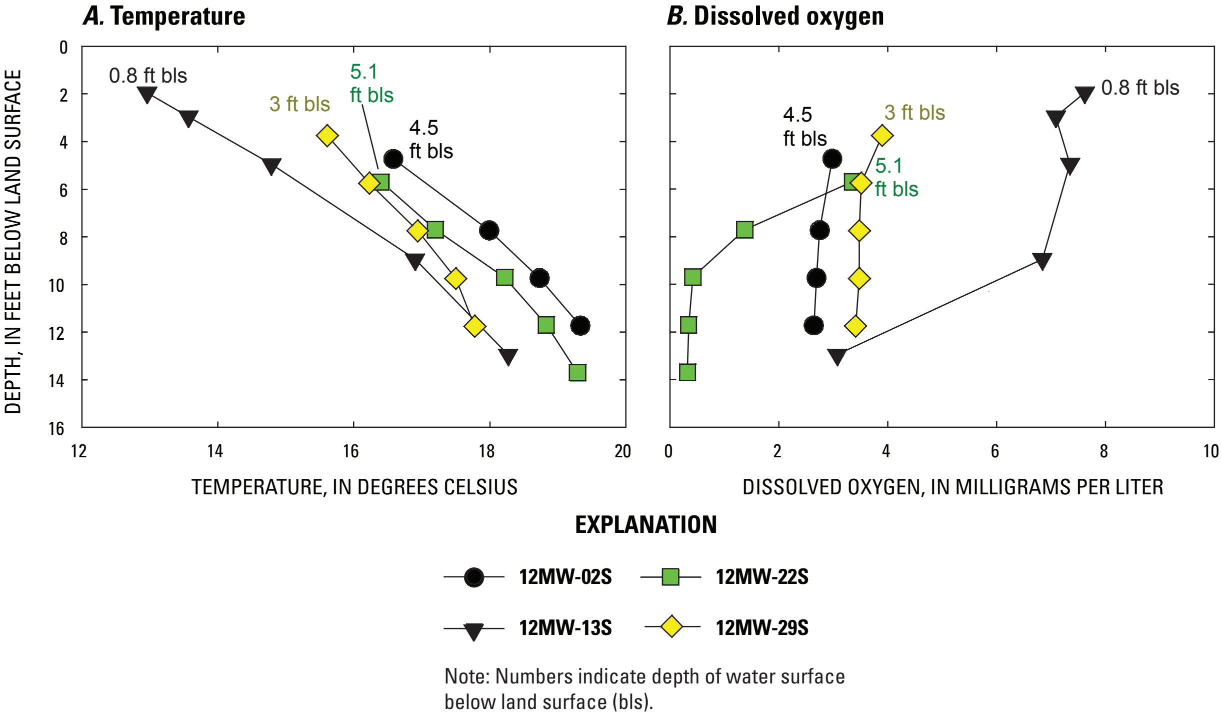


Figure 6. Temperature and dissolved-oxygen variations (January 2, 2005) and depths of water surface below land surface (January 25, 2005) in selected wells at Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina.

Depth to water is clearly not the only factor affecting convective transport of DO. For example, the February 2005 data from well 12MW-22S show that the DO in the 5-ft screened interval of the well was less than 0.5 mg/L (fig. 6*B*), despite the fact that the temperature profile was not substantially different than some of the other wells in figure 6*A*. This well differs from the other wells in figure 6 in that it is directly downgradient from a permeable reactive barrier (PRB) consisting of zero-valent iron, and the flow rates through well 12MW-22S are larger than through the other site wells discussed here, as determined by hydraulic gradients and hydraulic conductivity. The location of well 12MW-22S downgradient from the PRB resulted in a larger dissolved iron (Fe^{2+}) concentration relative to the other wells. The Fe^{2+} concentrations in well 12MW-22S ranged from 7.5 to 27.5 mg/L (August 2004–September 2005), with a concentration of 20 mg/L during February 2005. In contrast, the Fe^{2+} concentration in February 2005 was only 6 mg/L in well 12MW-13S and less than 2 mg/L in the remaining wells shown in figure 6. Dissolved Fe^{2+} is important because it can react quickly with DO to form iron hydroxides by the following reactions:

$$4Fe^{2+} + 4H^{+} + O_2 \rightarrow 4Fe^{3+} + 2H_2O \text{ , and} \qquad (1)$$

$$4Fe^{3+} + 12\,H_2O \rightarrow 4Fe(OH)_3 + 12H^{+} \text{ .} \qquad (2)$$

Therefore, the presence of Fe^{2+} can limit the amount of DO. These data indicate that the relatively high dissolved Fe^{2+} in well 12MW-22S aids in maintaining anaerobic conditions in the screened interval, despite convective movement of DO.

The presence of Fe^{2+} as a facilitating agent for scavenging DO is enhanced by the fact that the ground-water flow rate at well 12MW-22S is relatively large (24 to 38 feet per year [ft/yr]), whereas in wells 12MW-13S and 12MW-29S, the flow rate is probably less than 6 ft/yr. The ground-water flow rate at well 12MW-02S has not been quantified, but the rate is slower than at well 12MW-22S, and the Fe^{2+} concentration is typically less than 0.5 mg/L. Thus, the combination of high Fe^{2+} concentration and relatively high ground-water flow rate in well 12MW-22S removes oxygen from the convecting water.

Additional factors influencing oxygen circulation in wells can be seen by comparing a group of wells within 42 ft of each other. The temperature gradients are similar in wells 17PS-02, 17MW-06S, and 17MW-06D at SWMU17, NWS Charleston (fig. 7*A*); however, there are substantial differences in the DO circulation (fig. 7*B*). Wells 17MW-06S and 17MW-06D are horizontally separated by only a few feet, but the deeper well, 17MW-06D had greater than 2 mg/L of DO in the screened interval whereas the shallower member of the pair, 17MW-06S, had only about 0.6 mg/L of DO in the screened interval. One difference between the two wells is that the deeper well is poorly yielding relative to the shallow well. DO in the deeper, poorly yielding well probably circulates in the well with little exchange of solutes between the well bore and

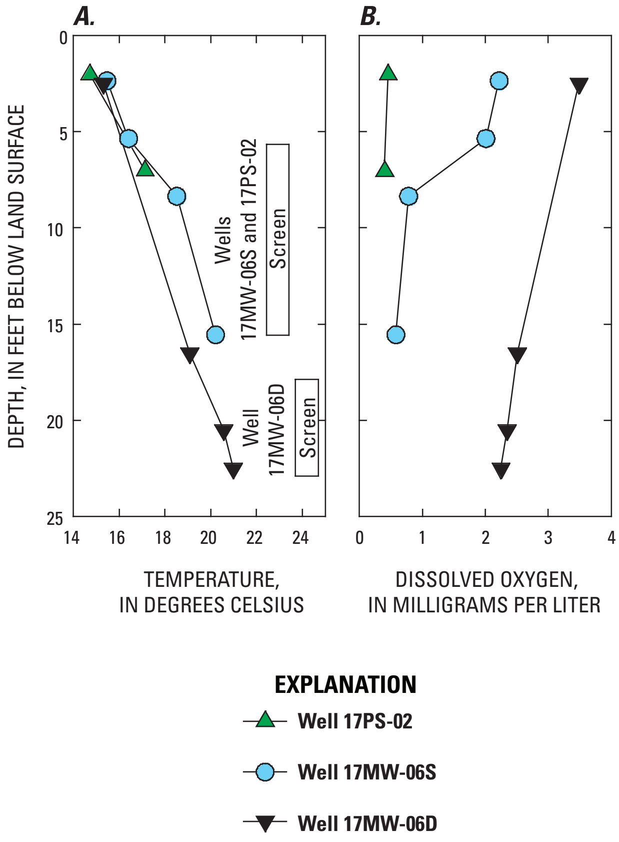


Figure 7. Vertical profile of temperature and dissolved oxygen in wells at Solid Waste Management Unit 17, Naval Weapons Station Charleston, North Charleston, South Carolina, March 8–9, 2005.

the aquifer. The shallower well, however, has a substantially larger yield, indicating greater potential for solute exchange between the aquifer and the well bore. Thus, this poorly yielding well can allow deeper circulation of DO by virtue of its limited ability to exchange water between the well bore and the aquifer.

Oxygen demand is an additional factor that influences oxygen circulation and is illustrated through the comparison of wells 17PS-02 and 17MW-06S. These wells are screened in the same aquifer at the same depth, approximately 42 ft from each other (fig. 7). While both wells exhibited a similar temperature gradient in March 2005 (fig. 7*A*), the DO in the shallow part of well 17PS-02 (0.46 mg/L) was substantially lower than at well 17MW-06S (2.2 mg/L) (fig. 7*B*). The main difference between the two wells is that well 17PS-02 is in the vicinity of an emulsified vegetable oil that was injected into the aquifer to facilitate contaminant degradation. In the injection area, the biological oxygen demand (BOD) was approximately 27 to 51 mg/L, and the chemical oxygen demand (COD) was about 128 to 144 mg/L (based on ground water collected from nearby well 17PS-03). In contrast, the BOD at well 17MW-06S was less than 2 mg/L, and the COD was only about 47 mg/L. Further, Fe^{2+} concentrations in well 17PS-02 were substantially higher (100 mg/L) than at 17MW-06S (approximately 5 to 10 mg/L). Thus, even though the temperature gradients indicate that convective circulation was taking place in the wells, the oxygen was scavenged rapidly from the circulating water when the oxygen demand was high.

The convection cells do not necessarily extend all of the way to the screened interval. Data from well 12MW-05D (SWMU12, NWS Charleston) in March 2005 show that the temperatures sharply increased with depth from near surface to a depth of about 19 ft (fig. 8). In this thermally unstable zone, the DO concentration was high (6–7 mg/L). At depths of about 29 ft and deeper, however, the water contained less than 0.5 mg/L of DO. The zone from the 29- to 38-ft depth shows little temperature change relative to the shallow part of the well. Therefore, possible reasons for the lack of DO transport to depths greater than 29 ft are: (1) the relatively minor temperature changes at those depths may be inadequate to support convection, and (2) low DO conditions may be maintained by exchange with aquifer water through the screen at 38.5 to 48.5 ft below land surface.

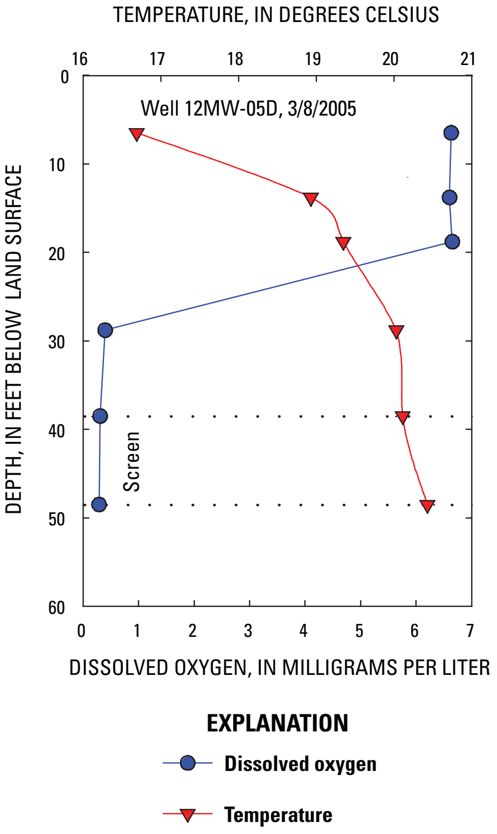


Figure 8. Dissolved-oxygen and temperature variations with depth in well 12MW-05D, Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina, March 8, 2005.

Implications for Passive Ground-Water Sampling in Wells

The convective movement of water in wells has potential implications for passive, or no-purge, and low-flow sampling approaches. If DO is convectively transported to the screened interval of a well open to an anaerobic aquifer, then it is clear that the DO content of the well does not represent the oxygen content of the aquifer. In such a situation, passive sampling for DO in the open interval of the well would not be appropriate. Further, because Fe^{2+} rapidly oxidizes and precipitates out of solution in the presence of DO, passive sampling for Fe^{2+} and similar metals also would not be appropriate in these wells without flow-limiting baffles. Passive sampling for Fe^{2+} and similar metals should not be used in wells in which convective movement of water extends to the well screen, regardless of whether DO remains in the convecting water, because the reduced DO content may be the result of metals precipitation.

Oxidation and precipitation of Fe^{2+} has further implications because the availability of ferric iron can cause the predominant terminal electron accepting process (TEAP) to shift to iron reduction from more-reducing TEAPs (Vroblesky and Chapelle, 1994). Thus, in a well without flow-limiting baffles, the predominant TEAP in the immediate vicinity of the well screen, as indicated by dissolved-hydrogen analyses, may differ from the predominant TEAP beyond the influence of the well screen.

The effect of DO circulation through thermal convection on other solutes, however, is less clear. Well 12MW-28S at SWMU12 is in an area where thermal instability causes convective flow within the well during cold months. The fact that well 12MW-28S has a water level of only 4.6 ft below land surface and has a relatively shallow screened interval (10 to 15 ft below land surface) indicates that convective movement of water probably was taking place in this well at the time of sampling in February 2006. A comparison of polyethylene diffusion bag sample (PDBS) results to low-flow sample results in February 2003 showed a close correspondence between all detected VOCs despite the convective flow (fig. 9). Convective flow apparently did not result in VOC loss relative to the low-flow sample.

No data were available for this investigation for comparisons of diffusion sampling for petroleum hydrocarbons in wells having convective transport of oxygen to the well screen. Aromatic hydrocarbons, however, readily degrade under aerobic conditions. If oxygen is transported to the well screen with the potential of diffusing or convecting from the well screen into the aquifer, then the zone in the immediate vicinity of the well screen may be more conducive to petroleum hydrocarbon degradation than in the aquifer farther from the well. Thus, there is the potential to underestimate petroleum hydrocarbon concentrations when passive sampling methods are used in a convecting well containing no impediments to vertical flow.

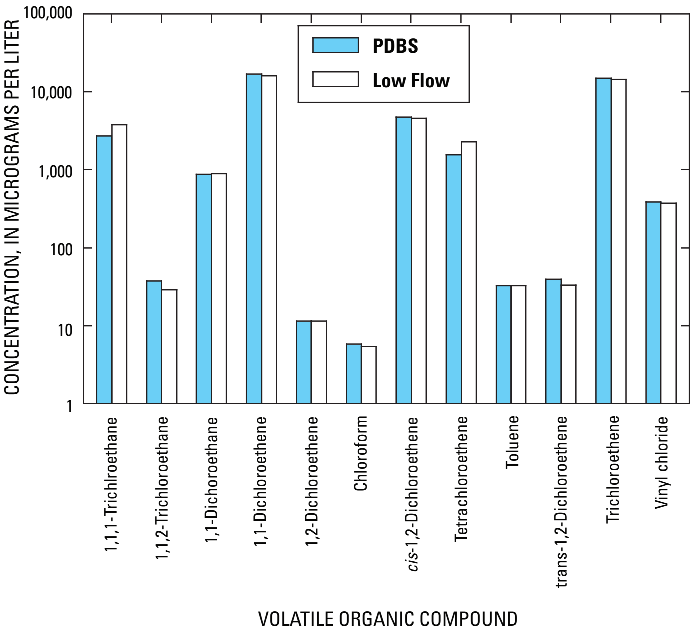


Figure 9. Concentrations of volatile organic compounds in polyethylene diffusion bag samples (PDBS) and low-flow samples at well 12MW-28S, Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina, February 13, 2003 (data from CH2MHill Constructors, Inc., 2003).

Implications for Low-Flow Ground-Water Sampling in Wells

Convective transport of DO in wells also can influence samples obtained by low-flow methods. Well 12MW-13S (NWS Charleston), discussed earlier, illustrates this point. This well was sampled by low-flow purging in January 2006. As shown in figure 6, this well is subject to convective transport of oxygen to the screened interval during January. While low-flow purging the well at about 200 mL/min, concentrations of DO gradually declined in the pumped water (fig. 10). After about 40 minutes of pumping, DO and temperature (fig. 10), as well as pH, turbidity, and specific conductance (data not shown) ceased their directional trend and varied (or oscillated) around a quasi-stable mean. For the next 28 minutes or so, the values fluctuated slightly up or down but did not substantially deviate from the oscillation mean, implying that they were oscillating about a flow-weighted average of water moving into the well through the screen (fig. 10). Although, the DO in well 12MW-13S was typically less than 0.3 mg/L, the low-flow data in January indicated that the concentration was approximately 1.2 mg/L. From a practical viewpoint, these values are substantially different because they represent the difference between anaerobic and aerobic degradation processes. It seemed unlikely that the aerobic conditions were

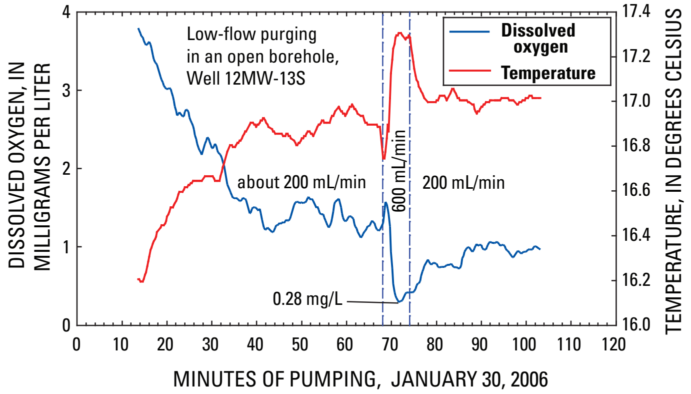


Figure 10. Changes in dissolved-oxygen concentration and temperature during low-flow sampling of well 12MW-13S, Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina, January 2006.

the result of local recharge of oxygenated water because a confining zone separates the aquifer from land surface and also because the nearest suspected recharge area was far enough away that it would require many years of transport to manifest itself at well 12MW-13S.

To clarify the source of the pumped water, the flow rate temporarily was increased to 600 mL/min (fig. 10). The initial response to the increased flow rate was a small and brief increase in DO concentration and a decrease in temperature at about 68 minutes of pumping, as would be expected from drawing down cooler, oxygenated water circulating in the well bore overlying the pump. This change was followed immediately (at about 69 minutes of pumping) by a sharp increase in temperature and decrease in DO concentration to the value typical for the aquifer. These data indicated that the water entering the pump at 600 mL/min at 69 minutes of pumping was almost entirely warmer aquifer water, and the previous indicator values represented a false stabilization. Further, the rapid change in indicator values to values more representative of the aquifer following the pumping-rate increase was not the result of simply removing the stagnant casing water more rapidly. If that were the case, then returning the flow rate to the original lower flow rate would not have caused an increase in the DO concentration. When the pumping rate was decreased to 200 mL/min, however, the DO concentrations in the pumped water increased to approximately 1 mg/L, and the temperature decreased (fig. 10). The data indicate that at the higher flow rate of 600 mL/min, the pump-induced movement of anaerobic aquifer water into the well screen was greater than the convective movement of oxygenated water in the well. The lower flow rate of 200 mL/min, however, allowed the aquifer water flowing in through the well screen to mix with the oxygenated water convecting to the pump and produced a mixture of water that erroneously implied that the aquifer was aerobic. Further verification was seen by resampling the well the same day by low-flow purging beneath a flow-through packer sealed above the screened interval. After about 30 minutes of purging at 190 mL/min, the DO isolated from the overlying unscreened casing water stabilized at 0.21 mg/L.

Similar results found during low-flow sampling in January 2006 can be seen in the low-flow sampling data from well 12MW-13S in January 2004. During this sampling event, the DO (fig. 11) and specific conductance (data not shown) took an uncharacteristically long time to approach stabilization at a pumping rate of about 200 mL/min. After about 120 minutes of pumping, the flow rate was increased to 980 mL/min. Following an initial brief increase in DO concentration, the DO in the pumped water decreased to the range characteristic of the aquifer. It is not likely that the decline in DO concentrations was merely the result of a more rapid removal of stagnant water because the temperature, which had been stable for at least 30 minutes, sharply increased when the pumping rate increased (fig. 11). The data imply that when pumping at 980 mL/min, the pumped water was predominantly warmer water from the aquifer. At the lower rate, however, attainment of a flow-weighted average from the aquifer was delayed, or perhaps prevented, by mixing with convecting oxygenated water overlying the pump.

Further evidence for convective movement of oxygenated water as an impediment to low-flow sampling can be seen in the comparison of the low-flow stabilization data from winter sampling and data obtained from the well 12MW-13S at other times of the year (fig. 12). In August 2004, May 2005, and September 2005, when the well was thermally stable, DO concentrations characteristic of the aquifer were obtained after purging for only 10 to 20 minutes at flow rates between 120 and 200 mL/min. In January 2004 and 2006, however, the well

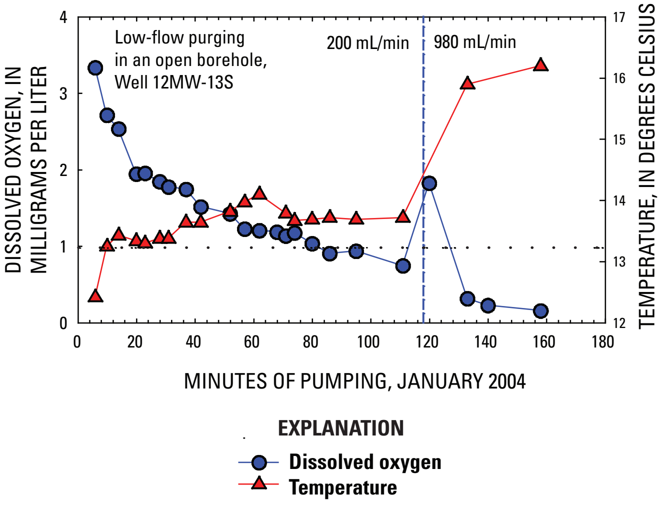


Figure 11. Changes in dissolved-oxygen concentration and temperature during low-flow sampling of well 12MW-13S, Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina, January 2004.

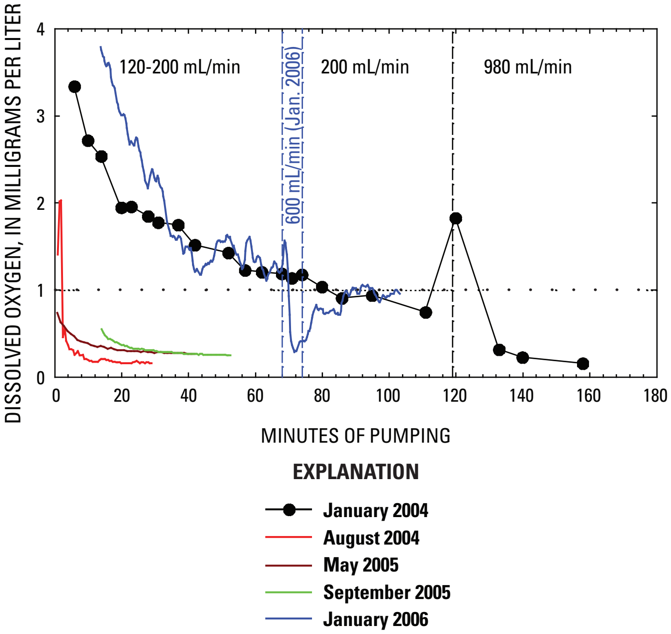


Figure 12. Comparison of changes in dissolved-oxygen concentration during low-flow sampling of well 12MW-13S at various times of the year, Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina.

had to be purged for a much longer time period than during summer months before DO concentrations representative of the aquifer were observed. Clearly, oxygen circulation in well bores can have a profound impact on low-flow sampling under field conditions. The detrimental influence of in-well convection on sampling under field conditions is consistent with laboratory investigations of Martin-Hayden (2000) in which a slight increase in temperature with depth (greater than 0.061°C per foot) in a well was sufficient for convective mixing of potentially altered casing water to overwhelm the pump-induced velocities during low-flow sampling (i.e. 220 mL/min).

Flow-Limiting Baffles to Mitigate Oxygen Convection

The field data from this investigation show that in some wells, there is a potential for convective circulation of oxygenated water to adversely affect passive and low-flow sampling. One alternative is to purge several casing volumes of water from the well prior to collecting a sample in an effort to remove the oxygenated casing water (Martin-Hayden, 2000). If convective circulation could be easily mitigated, however, then improvements on the quality of water samples from these wells could be attained without the need to purge substantial amounts of water. Well tests done as part of this investigation show that the convective flow can easily be reduced or eliminated.

To test the ability of an inflatable packer to mitigate convective circulation, an inflatable packer was placed in the well casing above the screen in well 12MW-29S at the Naval Weapons Station Charleston in February 2005. A DO sensor deployed below the packer showed that the DO in the well declined from greater than 3 mg/L prior to installing the packer to a range of 0.4 to 0.7 mg/L after packer installation. Clearly, an inflatable packer can effectively limit convective flow in the well bore. Small inflatable packers are inexpensive and can be easily deployed in wells. To eliminate the potential for oxygen bleed from the packer into the well, the packer can be inflated with an inert gas, such as nitrogen or helium. Thus, a disadvantage is that inflatable packers can be inconvenient to use if inert gas must be transported to the field site.

As a cheaper and simpler alternative to an inflatable packer, a homemade prototype of a simple baffle consisting of polyethylene disks on a threaded rod was deployed in well 12MW-29S in April 2006 (fig. 2). In a test prior to deploying the baffle, the top of the water column in the well was aerated and then chilled, which resulted in cold, oxygenated water moving to the well screen within an hour (fig. 13). In contrast, the same experiment the following week included deployment of the baffle. The temperature sharply decreased in the well water above the baffle, which was positioned at a depth of 8.25 ft. below land surface (fig. 14*A–D*). Directly below the baffle at a depth of 8.8 ft, however, the temperature did not noticeably change (fig. 14*E*), indicating that the convective cell had been blocked. Further evidence that the convective cell was blocked from the screen can be seen in the DO data. Prior to initiating the convective cell, the DO at a depth of 6.4 ft and below was about 0.4 to 0.6 mg/L (fig. 14*C*). Following initiation of the convective cell, however, the DO above the

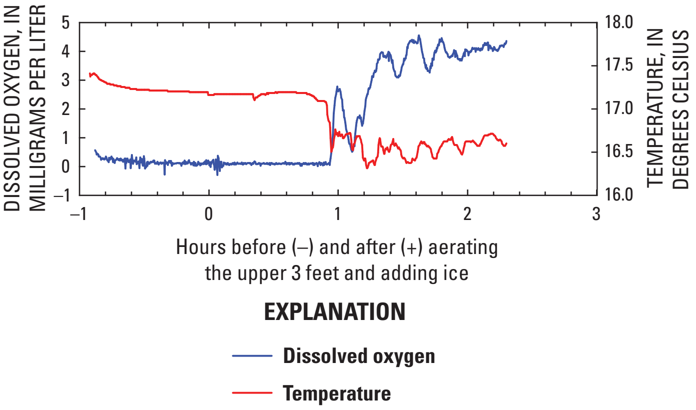


Figure 13. Convective transport of dissolved oxygen to a depth of 13 feet in well 12MW-29S during a field experiment that involved aerating the upper 3 feet of the water column and adding deionized ice to initiate convection, Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina, April 11, 2006.

baffle rose to approximately 5 mg/L (fig. 14*C*), while the DO below the baffle remained at about 0.4 to 0.6 mg/L (fig. 14*F*). Water-level changes and recovery observed during deployment of the baffle indicate that the simple baffle presented here was not adequate to eliminate advective flow as a result of head differences; however, the results of this test show that the baffle effectively blocked convective circulation of water.

These data show that simple in-well devices can effectively mitigate convective transport of oxygen. The devices can consist of inflatable packers to simple baffle systems. Johnson and others (2005) evaluated temperature sensors by using a simple homemade baffle consisting of foam-sleeve pipe insulation around a central rod. The data presented in the present investigation indicate that deployment of diffusion-type samplers below baffles may be a viable alternative for sampling wells influenced by thermal convection. Deployment of baffles with flow-through ports for pump tubing also may reduce some of the detrimental effects of convective well flow on low-flow sampling. Baffles left in place between sampling events may reduce the potential for convection-induced redox changes in the vicinity of the well screen.

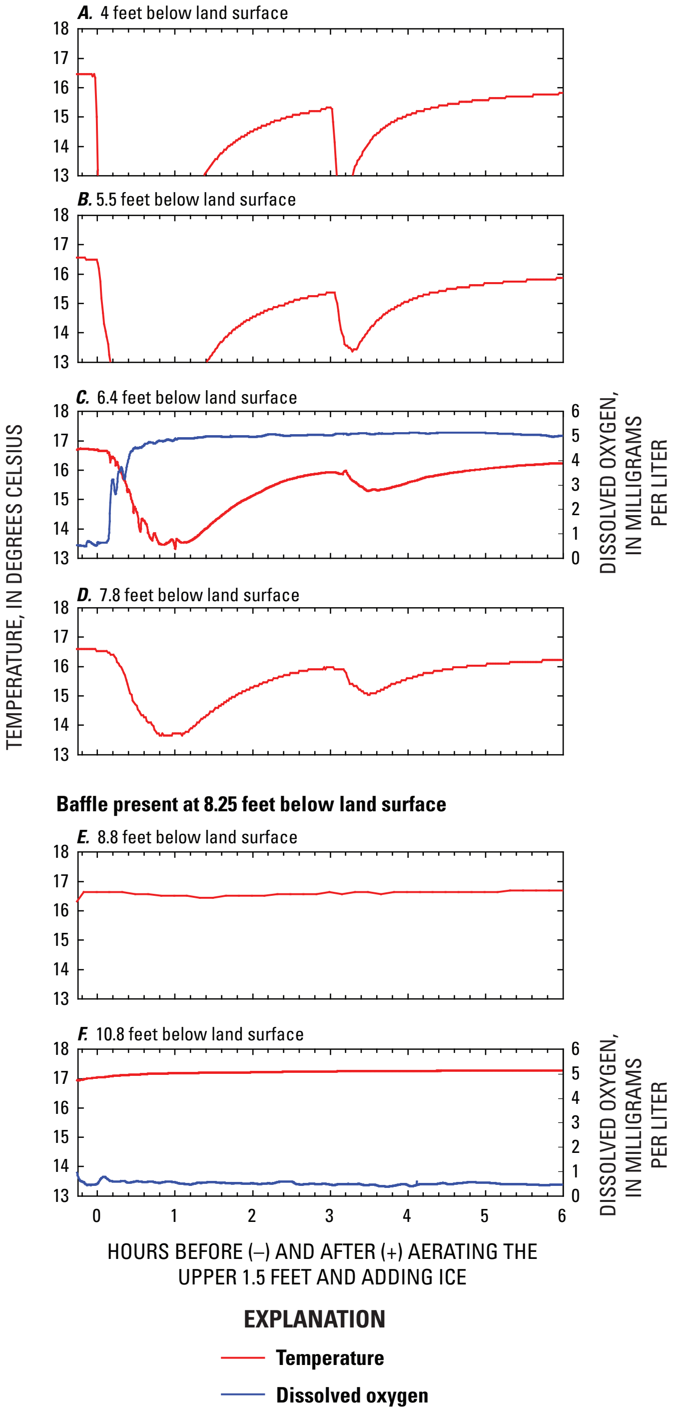


Figure 14. Temperature and dissolved oxygen at various depths in well 12MW-29S showing that a simple in-well baffle is sufficient to mitigate oxygen convection during a field experiment that involved aerating the upper 1.5 feet of the water column and adding deionized ice, Solid Waste Management Unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina, April 18, 2006.

Summary

Previous tests have shown that water within wells can develop convective circulation. Such convection was not traditionally considered to be problematic to sampling monitoring wells because sampling typically involved great disruption to the water column in the well. With the advent of low-flow and no-purge sampling, however, convective movement of DO within the well has the potential to influence the effectiveness of no-purge sampling techniques and to lengthen stabilization time during low-flow sampling, resulting in samples that may not be adequate indicators of solute concentrations in the aquifer.

The purposes of this investigation were to determine whether oxygen convection to monitoring well screens in anaerobic aquifers takes place under field conditions, to examine some of the factors influencing such convection, and to test the use of simple baffles as a tool to mitigate convection. The investigation was a cooperative effort between the USGS and the NavFac SE.

The water-temperature distribution in well MW-04D at Parris Island shows that during June through September, the shallowest water was warmer than the underlying water in the well, producing thermally-stable conditions in the shallow part of the well. By late August, the zone of thermal stability reached a depth of about 20 ft, with thermally unstable water below that. Beginning in late November, thermal instability developed in the shallow part of the well to a depth of 16 ft as the water near the top of the well became cooler than the water beneath it. The boundary between zones of thermal stability and instability shifted downward as the seasons progressed into the fall and winter.

In some wells examined during this investigation, DO was transported to the screened interval during the winter by in-well convection. In well 12MW-13S at the NWS Charleston, as the daily air-temperature range fell below the ground-water temperature, convection cells developed that transported oxygen to the sensor in the screened interval. Purging the well to obtain anaerobic ground water showed that the convection cells re-established oxygenated conditions in the well within 3 days.

Several factors influenced DO convection in the tested wells. Wells where the water level was near the surface were more affected by air temperature than wells where the depth to water was greater. The potential for convective transport to maintain aerobic conditions in a well appeared to be diminished as ground-water velocity increased through the well and as oxygen demand increased. Convective flow did not transport oxygen to the well screen when the top of the screened interval was deeper than the range of the convective cell.

The convective movement of water in wells has potential implications for passive, or no-purge, and low-flow sampling approaches. In the case of passive sampling, if oxygen is convectively transported to the screened interval of a well open to an anaerobic aquifer, then the oxygen content of the water in the well does not represent the oxygen content of the aquifer. In this situation, passive sampling for DO in a well without flow-limiting baffles would not be advisable. Further, because Fe^{2+} rapidly oxidizes and precipitates out of solution in the presence of oxygen, passive sampling for Fe^{2+} and similar metals also would not be appropriate. For solutes minimally affected by DO, however, passive sampling potentially can provide useful data regarding concentrations of these solutes in ground water. In the case of low-flow sampling, convective transport can substantially increase equilibration times and can cause false stabilization of indicator parameters, resulting in ground-water samples that are not representative of the aquifer conditions.

Data from this investigation show that simple in-well devices can effectively mitigate convective transport of DO. The devices range from inflatable packers to simple baffle systems. Deployment of diffusion-type samplers below such devices may be an effective way to sample wells. Deployment of baffles with flow-through ports for pump tubing also may reduce the detrimental effects of convective circulation on low-flow sampling.

In-well convection should not adversely affect samples collected when the well is thermally stable, typically during seasonally warmer months. In-well convection also may not be problematic in wells where the depth to water is large. Further investigation is needed to determine specific depths to water beyond which seasonally induced convection is insufficient to adversely affect sampling.

References Cited

Barcelona, M., Wehrmann, H.A., and Varljen, M.D., 1994, Reproducible well-purging procedures and VOC stabilization criteria for ground-water sampling: Ground Water, v. 32, p. 12–22.

CH2M Hill Constructors, Inc., 2003, Performance completion report, interim corrective measure, permeable reactive barrier, Solid Waste Management Unit 12, Naval Weapons Station, Charleston, South Carolina: Consultant's report to Naval Facilities Engineering Command, April 2003, 39 p.

Diment, W.H., 1967, Thermal regime of a large diameter borehole: Instability of the water column and comparison of air- and water-filled conditions: Geophysics, v. 32, no. 4, p. 720–726.

Ferguson, G., Woodbury, A.D., and Matile, G.L.D., 2003, Estimating deep recharge rates beneath an interlobate moraine using temperature logs: Ground Water, v. 41, no. 5, p. 640–646.

Gretener, P.E., 1967, On the thermal instability of large diameter wells—an observational report: Geophysics, v. 32, no. 4, p. 727–738.

Hales, A.L., 1937, Convection currents in geysers: Monthly Notices of the Royal Astronomical Society, Geophysics Supplement, v. 4, p. 122–131.

Johnson, A.N., Boer, B.R., Woessner, W.W., Stanford, J.A., Poole, G.C., Thomas, S.A., and O'Daniel, S.J., 2005, Evaluation of an inexpensive small-diameter temperature logger for documenting ground water-river interactions: Ground Water Monitoring and Remediation, v. 25, no. 4, p. 68–74.

Martin-Hayden, James, 2000, Controlled laboratory investigations of wellbore concentration response to pumping: Ground Water, v. 38, no. 1, p. 121–138.

Martin-Hayden, J.M., 2001, Characteristics of thermal instability and mixing within groundwater monitoring wells: Geological Society of America Annual Meeting, November 5–8, 2001, Boston, Massachusetts, 1 sheet.

Martin-Hayden, J.M., and Britt, S.L., 2006, Revealing the black box of groundwater sampling—effects of well-bore flow and mixing: 2006 North American Environmental Field Conference & Exposition, sponsored by The Nielsen Environmental Field School, Inc., and the University of South Florida Water Institute, January 10–12, 2006, Tampa, Florida, CD-ROM.

Salem, A.E., Taniguchi, M., and Sakura, Y., 2004, Use of temperature profiles and stable isotopes to trace flow lines: Nagaoka Area, Japan: Ground Water, v. 42, no. 1, p. 83–91.

Sammel, E., 1968, Convective flow and its effect on temperature logging in small-diameter wells: Geophysics, v. 33, no. 6, p. 1004–1012.

Sevee, J.E., White, C.A., and Maher, D.J., 2000, An analysis of low-flow ground water sampling methodology: Ground Water Monitoring and Remediation, Spring 2000, v. 20, no. 2, p. 87–93.

Shanklin, D.E., Sidle, W.C., and Ferguson, M.E., 1995, Micro-purge low-flow sampling of uranium-contaminated ground water at the Fernald Environmental Management Project: Ground Water Monitoring and Remediation, v. 15, no. 3, p. 168–176

Vroblesky, D.A., and Chapelle, F.H., 1994, Temporal and spatial changes of terminal electron-accepting processes in a petroleum hydrocarbon-contaminated aquifer and the significance for contaminant biodegradation: Water Resources Research, v. 30, no. 5, p. 1561–1570.

Manuscript approved for publication on September 25, 2006.

Final graphics prepared by James E. Banton.

Photocomposition and design by Kimberly A. Waltenbaugh.

For more information concerning the research in this report, contact Don A. Vroblesky, U.S. Geological Survey, Stephenson Center, Suite 129, 720 Gracern Road, Columbia, SC 29210, vroblesk@usgs.gov.