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RESPONSES TO COMMENTS ON WASTE MINIMIZATION AND GROUNDWATER SAMPLING EFFICIENCY: A NEW TECHNIQUE FOR PURGING GROUNDWATER MONITORING WELLS AT FEMP

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Department of Energy
Fernald Environmental Management Project
P.O. Box 398705
Cincinnati, Ohio 45239-8705
(513) 738-6357

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JAN 25 1994
DOE-0818-94

Mr. Graham E. Mitchell, Project Manager
Ohio Environmental Protection Agency
40 South Main Street
Dayton, OH 45402-2086

Dear Mr. Mitchell:

RESPONSES TO COMMENTS ON WASTE MINIMIZATION AND GROUNDWATER SAMPLING EFFICIENCY: A NEW TECHNIQUE FOR PURGING GROUNDWATER MONITORING WELLS AT FEMP

The subject report was issued December 17, 1993, to document the field experiments of our proposed technique, micro-purging, in order to minimize waste water and improve groundwater sampling efficiency at the Fernald Environmental Management Project (FEMP). Enclosed are our responses to comments issued by the Ohio Environmental Protection Agency (OEPA) on January 10, 1994.

On the basis of the successful experiment, as documented in the report and attached comments, the Department of Energy (DOE) requests that the OEPA grant approval to change the FEMP Groundwater Monitoring Program to include the micro-purging technique. Once approval is obtained from OEPA and the United States Environmental Protection Agency (U.S. EPA), appropriate site documents will be revised to reflect the new sampling procedure.

Your approval is requested so that we can implement micro-purging for the Spring sampling quarter.

If you have questions or require additional information, please contact William Sidle at (513) 648-3149.

Sincerely,

Jack Craig
Fernald Remedial Action
Project Manager

FN:Sidle

Enclosure: As Stated

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Recycled and Recyclable

cc w/enc:

M. Proffit, OEPA
R. Warner, DOE-FN
P. Pettit, FERMCO
AR Coordinator, FERMCO

cc w/o enc:

J. Thiesing, FERMCO

1. **Comment**

Specifically, how is the order of sensitivity and time for re-equilibration related to the pumping rate?

Response

The sensitivity is inversely proportional to the well purging (pumping) rate. Increased flow rates induce currents in the well and cause agitation and eventual mixing of the overlying stagnant water column with representative flow through the screened interval. Consequently it would require more time for the well to equilibrate. Below a 1.1 l/min purge rate in our wells, we measured no mixing between the overlying stagnant water column and the screened interval.

2. **Comment**

Is the 1 l/min flow rate based upon measured groundwater flow rates at the site?

Response

The maximum purging flow rate is not determined from local groundwater flow rates in the Great Miami aquifer, but is estimated from internal well hydraulics in type FEMP wells. Calculations from well screen dimensions and filter packs dictate that below a 1.1 l/min purge rate, overturn currents or eddying would be prevented in the overlying stagnant water column. Since all of our on-line monitoring wells have similar construction, we can predict that below a 1.1 l/min purge rate, representative groundwater samples can be collected in the screened interval without mixing with the overlying stagnant water column. Similar guidance exists in the recent literature as it applies to volatile organic constituents (VOC)(eg. Barcelona et al. 1994). Our experiments focused on the behavior of metals during variable purging events.

3. **Comment**

How is the water level measured to ensure that no drawdown occurs in the water column? How is the water level indicator probe inserted in the well so that the water column is not disturbed while measurements are obtained?

Additionally, how much "slop" is tolerated in Micro-Purging? If any drawdown is measured, then the water column has been disturbed. In this case, how much disturbance is considered tolerable, and how long must the monitoring well recover after such a disturbance in order to continue with Micro-Purging?

Response

Water elevations were measured with electronic water-level meters and confirmed with an independent water-level probe. Only the upper 3-6 in of the water column was in contact with the probe. The requirement to

isolate the stagnant water column essentially means that there is no mixing between this stagnant water interval and the screened interval. Minimal disturbance in the upper few inches from the insertion of the water-level meter had no influence on the water column. Lowering a probe a few inches into the well will not induce drawdown or significant eddying in the well compared to pumping at high flow rates.

No "slop" is tolerated in micro-purging. The point of the experiments was to determine the maximum purge rate such that overturn between the representative groundwater in the screened interval and the overlying stagnant water column would not occur. During our experiment, zero drawdown was observed at 1.1 l/min purging. Therefore the well does not have to re-equilibrate.

Once we purge the tubing, bladder pump, and flow cell (< 0.5 gal) we can draw a representative groundwater sample. The time of equilibration is theoretically zero but we delay drawing a sample until the tubing, bladder pump, and flow cell is purged. Depending on the depth of the well screen, times will be less than 3 min. Of course, the purge rates can be further reduced. As evidenced in our experiments, we purged at 500 ml/min and then sampled at 100-200 ml/min.

4. <u>Comment</u>

This table should be modified to include the type and size of sandpack used, type and installation details of the annular seals, and the thicknesses of both the sandpacks and seals.

<u>Response</u>

Micro-purging techniques are independent of the well construction standards. Only the relative flow purge rate will be influenced by well screen dimensions and filter packs. From our experiments we calculated that below a 1.1 l/min purge rate, overturn currents or eddying would be prevented in the overlying stagnant water column. Since all of our on-line monitoring wells have similar construction, we can predict that below a 1.1 l/min purge rate, representative groundwater samples can be collected in the screened interval without mixing with the overlying stagnant water column.

We included additional information on the sandpack, annular seals for your information: All four wells were constructed with 10-slot screens with filter packs made of type 10/20 silica sand. The filter packs were extended 5 feet above the top of the screens. For the two type 3 wells (with the screened interval located in the saturated zone), the annular seals are constructed of volclay grout placed from the top of the filter pack to the ground surface. For the two type 2 wells (with the screened interval that straddles the saturated zone), an additional 5-foot hydrated bentonite pellet seal is installed above the filter pack followed by volclay grout to the surface.

5. **Comment**

If Micro-Purging does not disturb the water column, why were packers installed for the tests? Will packers be installed in all Micro-Purged monitoring wells?

Response

Packers were not installed for the micro-purging tests. Packers already in wells were part of the pre-existing dedicated system. Packers are not required for micro-purging. We do not need to isolate upper zones of the aquifer as long as the overlying water column is not overturned. In fact an additional benefit of micro-purging is the elimination of packers. Upon approval of micro-purging no packers will be installed.

6. **Comment**

Why were VOC's not included in the analyte list? Before Ohio EPA can approve of this sampling technique, the effects of Micro-Purging on dissolved VOC's must be detailed.

Response

Our focus for the purging experiments were on metals, especially uranium, because of their potential for colloidal transport. Increased agitation causes turbidity levels to increase. As a result colloidal transport can be facilitated. Investigations by Kearl et al. (1992) have demonstrated this relationship when purge flow rates increase.

Overturn in the well that is responsible for agitation or mixing is also responsible for aeration (notwithstanding certain suction pumps which induce aeration). The earliest literature that we referenced in the subject report dealt primarily with preventing aeration and degassing due to purging and sampling protocols. We attached for your information a recent peer-reviewed publication by Barcelona et al. (1994) on VOC purging criteria. Their conclusions are identical with our premises for low purge flow rates.

7. **Comment**

Why were samples analyzed only in the FEMP lab? Why were duplicates not taken and sent offsite for analyses? Is this planned?

Response

Quality assurance samples were collected during the experiments to evaluate all analytical data. The laboratory was utilized for its convenience, cost savings, its familiarity with the FEMP groundwater monitoring program. We have no further plans to expand these experiments as the results were successful and in full agreement with other published micro-purging studies.

The FEMP laboratory is operated under the Remediation Support Operations Division. The experiment was conducted by the Groundwater Monitoring Section under the Environmental Safety and Health Division. Each division is operated under separate charters. This provides independence between the laboratory and the Groundwater Monitoring Section and eliminates potential bias.

Laboratory comparisons relate to an accuracy issue. The micro-purge experiment focused on the ability to obtain consistency with the laboratory results. The laboratory measured verses the actual levels of our selected parameters is not so much of interest as is the laboratory's ability to provide consistent procedural services. The FEMP laboratory routinely analyzes performance evaluation samples.

The intent of this experiment was not to involve inter-laboratory comparisons which would involve a dramatic overload of groundwater sampling. The success and applicability of the micro-purge technique has been well proven and documented in the literature. The experiment that was conduced was only to determine the technique's utilization at the FEMP.

8. **Comment**

It would seem that indicator parameters would be indicative of disturbance of the water column. How quickly was stabilization achieved and was there any fluctuation during sampling?

Response

Some indicator parameters are sensitive to disturbances in the water column. The literature cited in the subject report and from our experience, suggest that four indicator parameters are most useful. These include pH, temperature, dissolved oxygen, and specific conductance. The literature suggest that pH and temperature are good indicators of overturn. The pH and temperature contrast between the stagnant water column and the groundwater flow through the screen will be indicated. Dissolved oxygen and specific conductance will be more subject to minor eddying immediately after pumping commences and will likely display sudden and larger shifts as overturn continues within the screened interval. Small shifts will occur however even if overturn is not present because oxygen and dissolved solids are not homogeneously distributed in a groundwater regime.

Our data displayed on time-series plots in the subject report indicate that stabilization was immediate to less than 1 min. We interpret the minor fluctuations of dissolved oxygen and specific conductance as due to the natural groundwater flow through the screen.

9. **Comment**

What explanation of the fluctuation of indicator parameters does DOE offer? If samples were representative of in situ ground water, why would these parameters fluctuate?

Response

Please see response #8.

REFERENCES

KEARL, P. Korte, N. and Cronk, T.A. 1992. Suggested modifications to ground water sampling procedures based on observations from the colloidal borescope. Ground Water Monitoring Review, V. 12, n. 2, pp. 155-161.

BARCELONA, M.J., Wehrmann, H.A., and Varljen, M.D. 1994. Reproducible well-purging procedures and VOC stabilization criteria for ground-water sampling. Ground Water, V. 32, n. 1, pp. 12-22.

Reproducible Well-Purging Procedures and VOC Stabilization Criteria for Ground-Water Sampling

by Michael J. Barcelona[a], H. Allen Wehrmann[b], and Mark D. Varljen[c]

Abstract

Recent research has confirmed that low flow rate purging (i.e., ~1 l/min) is a valid technique for 2" (5 cm) diameter monitoring wells with short screened intervals. The use of low flow, dedicated pumping devices for purging and sampling minimizes both the disturbance of stagnant water in the well casing and the potential for mobilization of particulate or colloidal matter which could lead to sampling artifacts. In addition, these techniques allow the use of purging indicator parameters (e.g., dissolved oxygen and specific conductance) to determine when to collect a sample for volatile organic compound (VOC) determinations. Detailed results from a monitoring network in a sand and gravel aquifer contaminated by organochlorine solvents support these findings. Recent publications on monitoring well hydraulic behavior and considerations of mass averaging effects due to pumping also support the use of low flow rate, minimal drawdown purging procedures to achieve reproducible sampling results. The suggested procedure includes documenting purging indicator parameters while purging with dedicated devices at low flow rates with minimal drawdown. This sampling method is less time-consuming and reduces the need to handle large volumes of purge water since VOC concentrations, O_2, and specific conductance values stabilized consistently in less than one bore volume.

Introduction

The common goal in the development of ground-water sampling procedures and monitoring network design criteria for detection, assessment, and research investigations is to collect samples which are representative of actual hydrogeochemical conditions. Considerable progress has been made in ground-water sampling research which has paid dividends in the improved quality of monitoring efforts. New field methods for gas, solid, and water sampling have been developed and refined to supplement the information which can be obtained through the use of monitoring wells alone. However, substantial gaps remain in the methods available to ensure that water samples from wells are consistently representative of site conditions. Numerous investigators have pointed out the necessity of three-dimensional, discrete sampling in order to account for vertical and horizontal gradients in chemical concentrations, oxidation-reduction conditions, and subsurface hydrogeologic properties (Back, 1966; Gillham et al., 1983; Barcelona et al., 1989a; Sudicky, 1986). Integrated solid sampling and the use of vertically discrete sampling points (Hoffman and Dresen, 1990; Pickens et al., 1978; Ronen et al., 1987) provide the required level of spatial detail and the ability to determine hydraulic conductivity by various methods in long-term water sampling efforts. As the number of sampling points increase during an investigation, sampling and analysis costs increase significantly and the efficiency of information collection may be strained.

The need to conduct more detailed, reliable sampling efforts at low cost has led to a staggering variety of well-purging and sampling techniques. The use of combinations of devices for sampling at different locations at some sites may make it difficult to compare chemical data. Methods to "speed up" the purging of wells by high flow rate pumping pose a challenge to consistent, if not representative, sampling efforts in heterogeneous, transmissive glacial aquifers.

The recent work of Puls et al. (1992), and Powell and Puls (1993), has shown clearly that high flow rate pumping (i.e., in excess of "natural" flow through the screen), causes significant turbidity and suspended particulate artifacts. This is particularly true of nondedicated devices which must be inserted and removed from wells. The consequences of overpumping may include erroneously high turbidity and total metal levels as well as the potential for damage to the sand pack of the monitoring well. In the cases noted above, the effects on sampling results can be on the order of a factor of 10 or more. These levels are significantly higher than those associated with controlled sample handling and analysis procedures (Barcelona and Helfrich, 1992; Puls and Barcelona, 1989a, 1989b).

The effects of well design and construction (i.e., location, screened interval, and sand pack) as well as high volume pumping or bailing can also lead to order-of-magnitude errors in dissolved chemical constituent data (Schmidt, 1982). Robbins (1989) has shown convincing evidence that erroneous concentration data at a site can result from purging partially penetrating monitoring wells, particularly with long (i.e. > 2 m) and variable length screened intervals. The well design, location, and purging effects that

[a]Institute for Water Sciences—Department of Chemistry, Western Michigan University, Kalamazoo, Michigan 49008.
[b]Illinois Water Survey Division—Department of Energy and Natural Resources, Champaign, Illinois 61820.
[c]Hart-Crowser Inc., Seattle, Washington 98102.
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Robbins described can result in grossly misleading estimates of contamination extent and distribution. In effect, chemical data collection from a network of wells with different screened intervals and depths may be as useless as the corresponding potentiometric surface map. Robbins and Martin-Hayden (1991) have extended this work recently to a detailed evaluation of monitoring well hydraulics. They emphasized the combined influences of bailing or pumping induced mass-averaging effects due to mixing in the well and screened interval. In this work and its field validation (Martin-Hayden et al., 1991) the authors demonstrated, using mass-balance techniques, the extreme sensitivity of water chemistry results to well construction, purging procedure, vertical solute concentration distributions, and the hydrogeologic properties of the aquifer. Further, they established the futility of the use of bailers to purge wells due to composite averaging and the nonsteady water removal rates which promote mixing of water across the screen. These contributions demand a careful reexamination of recommended procedures for monitoring well network design, construction, and operation. Inconsistent and biased data collection remains a serious issue for the interpretation of data for trend analysis and remedial action performance in the operation of new or existing monitoring networks.

There is a need for reliable criteria for sampling monitoring wells. Rules of thumb applied to purging volume requirements (e.g., three to five "well" volumes) do not necessarily yield representative samples. Stabilization of indicator parameters at fixed rates of pumping, however, may provide consistent results. Valuable intepretations may be achieved when the monitoring well hydraulics are integrated with chemical data collected during pumping (Keeley, 1982; Keeley and Wolf, 1983). The goal of the present investigation was to evaluate the use of easily measured purging indicator parameters during well purging as consistent criteria for the stabilization of volatile organic compounds (VOC) prior to sampling. It should be recognized that firm criteria for indicator parameter stabilization cannot be set a priori due to the variability in aquifer properties and monitoring well hydraulics (Robbins and Martin-Hayden, 1991; Robin and Gillham, 1987).

Experimental Procedures

Site Description

The field site is located within an approximate 1 square mile (2.6 km^2) area in southeast Rockford, a city of over 100,000 people in north central Illinois (Figure 1). The site is underlain by an extensive glacial outwash sand and gravel water-table aquifer (Wehrmann et al., 1988; Berg et al., 1984). This area is bordered on the west by the Rock River and on the east by uplands of Galena-Platteville Dolomite which form at the border of the preglacial Rock Bedrock valley. The purging study site is centrally situated within a portion of a larger 3.5 square mile (9 km^2) study area designated as the Southeast Rockford National Priority List (NPL) Site. Principal contaminants include: 1,1,1 trichloroethane (1,1,1 TCA); 1,1 dichloroethane (1,1 DCA); c-1,2 dichloroethylene (cis-1,2 DCE); trichloroethylene (TCE); and 1,1 dichloroethylene (1,1 DCE). The area has been

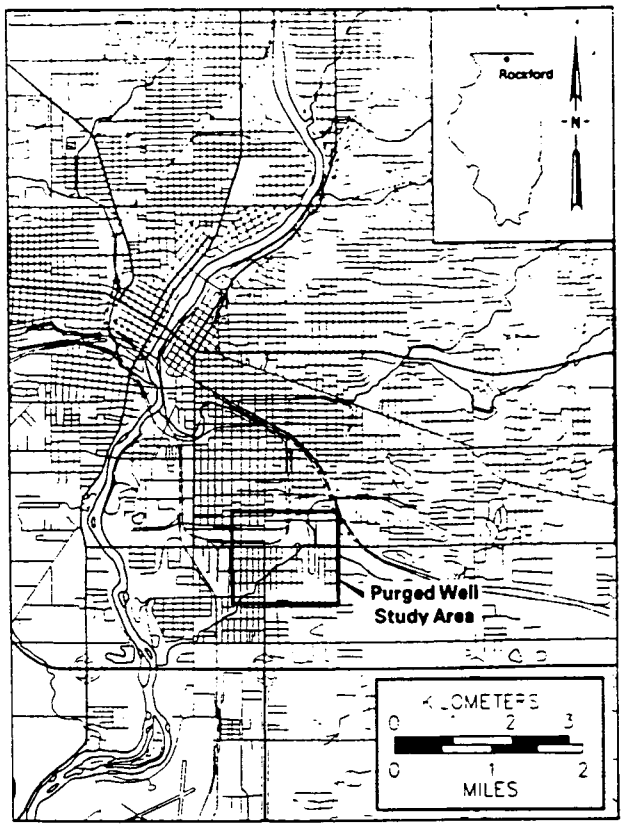

Fig. 1. Location of purged well study area in southeast Rockford, Illinois.

active residentially and industrially for more than 100 years, and this mixed zoning resulted in the extensive contamination of over 200 private and public water-supply wells. The total dissolved VOC distribution (i.e., the total of the five major compounds above) shown in Figure 2 was obtained by synoptic sampling of over 40 wells within the NPL Site area.

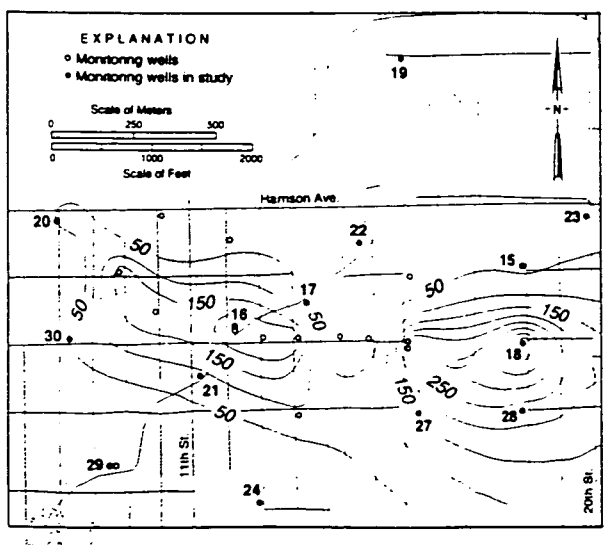

Fig. 2. Enlarged view of the purged well study area showing locations of monitoring wells used in the study and total VOC concentration contours derived from May 1991 sampling of all monitoring wells in the area.

Well Construction and Development

The monitoring network in the study area shown in Figure 2 consisted of more than forty 2" (5 cm) diameter wells which were constructed by hollow-stem auger drilling techniques. The wells were designed with short-screened intervals (mainly 5 ft; 1.5 m) approximately (15 ft; 4.5 m) below the static water level of the aquifer.

The wells were constructed of 2 inch (5 cm) i.d., 0.010" (0.25 mm) slot, wire-wound, flush-threaded, stainless steel (SS) screen and riser, with polyvinylchoride riser above the water table. Due to the clean and homogeneous nature of the sand and gravel at this site, the formation was allowed to collapse around the casing and screen as the augers were removed from the hole. The completions were sealed against surface infiltration by a minimum three feet (~1 m) of granular bentonite seal at the water table, and a cemented surface flush mount vault or a 6" (15 cm) cylindrical steel well protector. The wells were developed by pumping with compressed air or an electric submersible pump at effective rates of 5 to 10 gallons per minute (20-41 l/min) with surging, until the pumped water was visually free of suspended particulates. Data collected at selected wells are presented in the results section dealing with development. The majority of the wells selected were constructed at least one year before the purging study was initiated. All wells were sampled with dedicated bladder pumps at quarterly intervals during the course of a long-term evaluation of spatial and temporal variability of volatile organic compound concentrations at the site.

Sampling Procedures

The sampling procedures described in previous publications were followed in detail (Barcelona et al., 1989a, b). Briefly, each well was unlocked and measurements of water level and in situ temperature using a thermistor probe (Omega Instruments) were taken. The sampling connections were made and the dedicated polytetrafluoroethylene bladder (QED, Inc.) pump with the intake set at midscreen was started. Fluoroethylene polymer (FEP) discharge tubing (½" o.d.) from the bladder pump was directed to a three-way SS valve which led to either: (a) an FEP sampling tube, (b) a discharge line to waste, or (c) a flow cell (Garske and Schock, 1986) equipped with dissolved oxygen, pH, temperature, and specific conductance sensors. The flow rate was maintained at 1.0 ± 0.1 l/min, and cumulative volume pumped was measured at each well. At least one sample was spiked with a combined standard solution to evaluate storage and analysis error for each sampling trip. Pumping and sampling were continued until all of the indicator parameters stabilized to within ± 0.2 mg O_2/l, ± 0.10 pH units, ± 0.1 C° and ± 10.0 μS/cm over a successive bore volume. A bore volume was taken to be the water included in the sand pack, screen, and casing of the well. Intensive sampling for the purging study was conducted in February 1991.

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Analytical Procedures

Field analytical procedures were calibrated with: (a) standard solutions in the case of pH and conductance, and (b) sulfite-treated water (0.0 mg O_2/l) and air-saturated water for O_2. The samples were transported and stored on ice until arrival at the laboratory. The samples were prepared within 24 hours for static headspace gas-chromatography with simultaneous photoionization (PID)/electrolytic conductivity detector (ELCD) analyses. Each sample was analyzed in duplicate, with each subsample receiving a spike of appropriate internal standard for calibration purposes prior to being sealed in aluminum-crimped-top headspace vials (Tekmar 7500). Laboratory standards and blanks were used to calibrate relative molar response factors for all the constituents of interest. A standard was introduced into the analytical sequence after every ninth sample. Field blanks, standards, and spiked samples were analyzed with samples to control for storage, handling, and analytical errors. The analytical concentrations were corrected for dilution (if necessary). They were not corrected for total recovery since the recoveries of field-spiked samples and analytical standards over time were within acceptable control limits.

Results and Discussion

Well Development

Well development is a critical step in the construction of monitoring wells through which hydraulic connection is established with the formation over the screened interval. In selected instances, the effect of compressed air development on the dissolved oxygen content of the formation water was checked by pumping through the flow cell at flow rates of 1.0 to 1.5 l/min before and after development. The stable values prior to air development compared favorably with those measured after development as well as to the annual mean concentrations determined over the year following well construction (Table 1). The results suggest that the local geochemical disturbances due to well construction and development can be minimized by continued pumping to stable dissolved oxygen readings. It would appear that positive displacement pumping should be done after compressed air development to remove oxygenated water. In less permeable screened formations, the effects of compressed air pumping may differ from our results, and care must be exercised in the choice of suitable development techniques. Measurements of the indicator parameters at this point also begin the documentation of the purging behavior for each well. These initial data are useful in the estimation of practical stabilization limits prior to beginning actual routine sampling.

Hydraulic Conductivity Testing

All of the wells in the extended network, including those selected for the purging study, were subjected to aquifer hydraulic conductivity determinations after development. Hydraulic conductivities were determined by analysis of water-level response to slug tests performed through a casing pressurization technique similar to that described by Prosser (1981) and modified by Kelly (1990). The casing pressurization technique was used because the highly conductive outwash sands at this site allow very rapid water-level response to induced head changes (e.g., often less than 10 seconds for 7 to 8 feet of water-level displacement). A

Table 1. Dissolved Oxygen Values Associated with Compressed Air Well Development

Well #	Bore volume (l)	Dissolved oxygen concentrations (mg/l): Initial*	Pumped to stable values**	After compressed air development*	Pumped to stable value**	Oxygen annual mean ± (rsd%)
15	16.7	2.2	2.00 (53)+	8.00	2.50 (10)+	1.80 ± 0.85
16	22.5	3.5	2.75 (104)	6.50	3.75 (49)	2.20 ± 0.35
17	22.4	3.80	2.70 (96)	5.31	2.59 (21)	2.23 ± 1.40
19	19.8	4.20	3.35 (11)	10.5	3.25 (59)	2.75 ± 1.21
20	26.0	1.10	0.3 (110)	4.5	0.2 (71)	0.23 ± 0.15

*Pumped at 1 to 1.5 l/min with submersible pump to flush flow cell.
**Pumped at 20 to 41 l/min with submersible pump to stable value.
+Volume pumped in liters.
rsd = relative standard deviation of mean values.

microcomputer-based data acquisition system developed at the Illinois State Water Survey was used to collect water-level response data. Each well was tested in triplicate and the resulting data were analyzed by methods described by Bouwer and Rice (1976).

A summary of the screened interval depth, depth to water, stored water volume, description of geologic material encountered at well completion depth, and hydraulic conductivity for each well is shown in Table 2. All hydraulic conductivities displayed in Table 2 are averages of Bouwer and Rice analyses for the three tests conducted at each well. The hydraulic conductivities derived from the well pressurization tests were within expected ranges for the materials encountered and range from 2.6 to 66 $\times 10^{-3}$ cm/sec.

Well-Purging Behavior

The monitoring wells in the network shown in Figure 2 were purged and sampled by low flow-rate pumping at quarterly intervals after construction. For this study, the subset of 13 wells constructed in 1989 (Table 2) was selected for purging study. The "dead" volume in the dedicated bladder pump, water discharge line, and flow cell was about one liter. In this sense, the earliest that a well could show an indication of parameter stabilization would be approximately two liters which would provide at least two cell volume flushes of water from the screened interval of the well.

Triplicate VOC samples (i.e., 8 to 10 per well) were collected at intervals of ~ 1 to 3 l by diverting a portion of the flow to an FEP sampling line at flow rates of ~ 100 ml/min. Pumping was frequently continued beyond three bore volumes to document complete stabilization. It was rarely necessary to pump the wells beyond the two bore volumes at ~ 1 l/min (entrance velocity ~ 0.2 ft/min; 6 cm/min) to achieve indicator parameter stabilization. Due to the steady discharge/recharge cycling of the bladder pumps, it was

Table 2. Study Well Descriptions and Hydraulic Conductivity Results

Well #	Screened interval (ft bls)	Depth to water (ft bls) 11/90	Depth to water (ft bls) 2/91	Bore volume* (liters) 11/90	Bore volume* (liters) 2/91	Aquifer material at screened interval	Hydraulic conductivity (cm/s)
15	45-50	42.54	41.98	16.3	16.7	Sandy clay	8.0×10^{-3}
16	42.5-47.5	30.31	30.02	22.4	22.5	Gravel, coarse sand	3.11×10^{-2}
17	40-45	28.10	27.72	22.2	22.4	Gravel, coarse sand	3.06×10^{-2}
18	79-84	65.67	65.01	23.1	23.5	Fine sand	1.70×10^{-2}
19	44.3-49.3	36.61	36.22	19.6	19.8	Med. sand	2.12×10^{-2}
20	48.3-53.3	30.40	30.20	25.9	26.0	Med. sand	6.59×10^{-2}
21	41.4-46.4	28.55	28.27	22.8	22.9	Gravel, coarse sand	4.29×10^{-2}
22	40-45	30.90	30.54	20.4	20.7	Gravel, med. sand	3.96×10^{-2}
23	55-60	37.05	36.31	25.9	26.4	Silty, coarse sand	2.12×10^{-2}
24	37.7-42.7	32.28	32.00	18.1	19.3	Light med. sand	1.46×10^{-2}
27	67-72	50.61	50.11	18.5	18.8	Med. coarse sand	1.92×10^{-2}
28	96.8-99.3	74.25	73.62	26.9	27.3	Fine-med. sand	2.60×10^{-3}
29	31.6-36.6	22.16	21.98	20.7	20.8	Clean coarse sand	5.18×10^{-2}
30	45.1-50.1	34.29	34.16	21.5	21.6	Coarse sand	3.63×10^{-2}

*Bore volume = standing water in casing/screen and borehole around screen (Robbins and Martin-Hayden, 1991).
bls = below land surface.

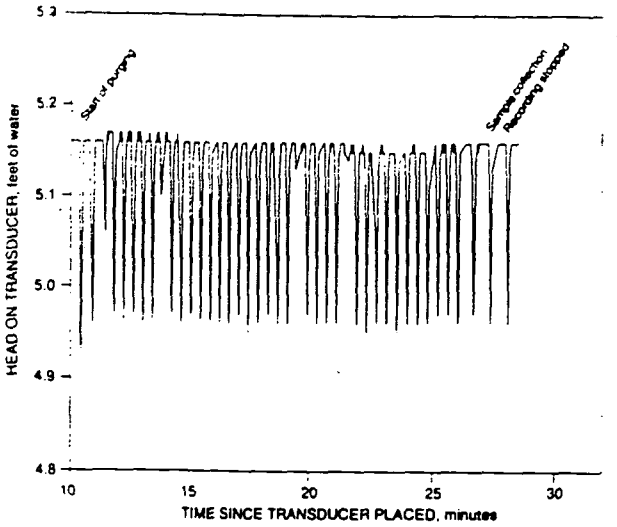

Fig. 3. Typical water-level response in a southeast Rockford monitoring well during purging and sampling with a bladder pump.

possible to achieve control over flow rates within ± 0.1 l/min. Indicator parameter readings were taken (i.e., 12 to 20 per well) from the meters connected to the electrodes in the flow cell during the middle to end of the bladder pump discharge period. In selected cases, the water levels in the wells were monitored during pumping with either an electric drop-line or a downhole transducer linked to a laptop computer. An example of water-level response during pumping is shown in Figure 3. The bladder pump action caused cycling of water levels of ~ 0.2 to 0.3 ft (0.06–0.09 m) during pumping but no significant net drawdown was observed in any of the wells at the conclusion of sampling operations.

Indicator Parameters and VOC Stabilization

Dissolved oxygen and specific conductance (Ω^{-1}) readings were found to be the most useful field indicator parameters for stabilization of background water chemistry during purging. The pH and temperature readings achieved stable values almost immediately (i.e., within 1 to 2 l) during purging in all cases. The temperature readings at the flow cell differed from the downhole probe values by 3 to 5 C° due to seasonal changes in air temperature even though the sample discharge line from the wellhead to the cell was insulated with foam tubing. An example of well-purging to stabilization is shown in Figure 4 for well #18. Identification of the initial volume to stabilization (V_i) for each well and parameter was done by manually extrapolating to the intersection of lines on the stabilization plateau and rising or falling limb of the concentration curve as a function of volume purged.

The median and range of maximum and minimum percent bore volumes to stabilization for the indicator parameters and VOCs for the study wells are shown in Figure 5. The box and whisker plots show the median as a vertical line and the limits of the box as the upper and lower quartiles of the distribution. The "whiskers" represent the minimum and maximum stabilization volumes for all study wells. The average stabilization volume of at least four quarterly sampling events for all of the wells was less than one-half of a bore volume. The volume to stabilization for O_2 and conductance exceeded one bore volume in only one instance out of 64 quarterly sampling events.

The average initial concentrations of dissolved O_2 were significantly higher (~ 6x) and those for Ω^{-1} significantly lower (~ 0.7x) than the final purged values. The values for the ratio of the initial concentration C_o (unpurged) to the final purged concentration are shown in Table 3. These

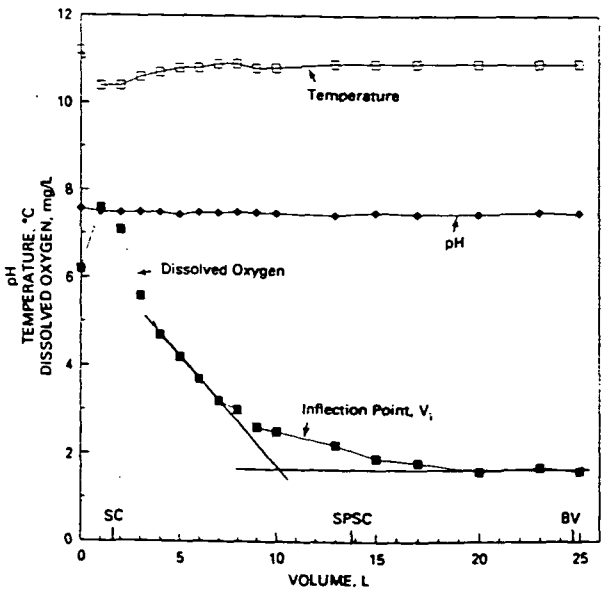

Fig. 4. Plot of typical purging behavior of temperature, pH, and dissolved O_2 (SC = volume of water in screened interval; SPSC = volume of water in screened interval and sandpack; BV = volume of water in well including screen and sandpack).

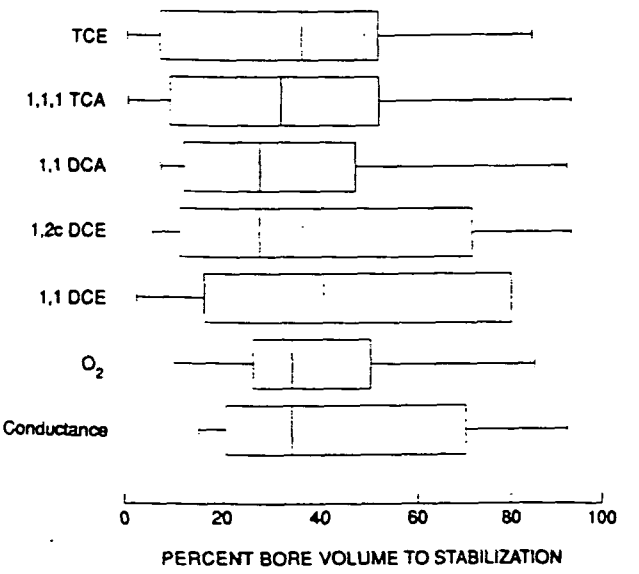

Fig. 5. Box and whisker plots of the percent of bore volume purged to reach stabilization for the indicator parameters and VOCs.

Table 3. Compilation of Initial to Final Concentration Ratios

A Well	B Oxygen	C Conductance	D 1,1DCE	E 1,1DCA	F 1,2cDCE	G 1,1,1TCA	H TCE
15	3.05	0.96	1.00	1.04	0.92	0.80	1.07
16*	N.A.	0.98	0.21	0.25	0.27	0.24	0.27
16	N.A.	N.A.	0.90	1.06	0.83	1.12	0.85
17	1.44	0.77	0.76	0.98	0.65	0.95	0.66
18	3.88	0.33	0.48	0.78	0.64	0.63	0.80
19	1.25	0.69	0.20	—	—	0.53	—
20	49.00	0.43	0.95	0.99	1.06	0.84	—
21	N.A.	0.90	1.23	1.07	1.34	1.20	1.46
22	4.30	0.80	1.40	0.87	0.94	1.10	1.21
23	1.03	0.95	1.10	1.17	1.09	1.22	0.91
24	1.61	0.10	—	—	—	0.41	0.08
27	1.54	0.68	0.72	0.78	0.71	0.77	0.70
28	2.17	1.04	0.50	0.90	0.82	0.70	0.90
29	1.68	0.62	—	—	—	1.07	1.10
30*	N.A.	N.A.	0.02	0.01	0.01	0.78	0.84
30	1.10	0.26	1.35	0.98	0.94	1.14	1.05
Avg	6.00	0.68	0.77	0.84	0.79	0.84	0.85
Stdev	13.58	0.30	0.44	0.34	0.35	0.29	0.36

N.A. = Data not available.
— = Compound not detected.
* = Preliminary purging results for 11/90 sampling.

observations are consistent with the exposure of the standing water in the well to oxygen and the loss of CO_2 resulting in oxidation and precipitation of dissolved solutes. These marked differences between prepurged and purged concentration values for the indicator parameters indicate the need to purge wells prior to sampling. The following discussion treats these observations more quantitatively as well as those regarding purging behavior of the VOCs.

The ratios of the initial to final (i.e. postpurging) concentrations of VOCs provided in Table 3 show the effects of degassing on stored water. The ratios for the five principal contaminants ranged from 0.01 to 1.46. The higher ratios are skewed somewhat by the variable, low concentrations of VOCs in wells 21, 23, and 30. The apparent 15 to 23% lower initial values due to outgassing of the volatiles underscore the need to purge monitoring wells even in this type of transmissive hydrogeologic environment where one might expect the screened interval to be renewed by flow (Robin and Gillham, 1987; Powell and Puls, 1993). The observed differences between the initial and final concentrations are modest in comparison with those reported by some previous workers (Smith et al., 1988; Barcelona and Helfrich, 1992; Gibs and Imbrigiotta, 1990; and Chou et al., 1991). Stagnant water samples from monitoring wells have been found to be significantly lower in volatile organic compounds than those measured after purging in a range of hydrogeologic settings.

Low volume, low flow-rate pumping was sufficient for stabilization of O_2 and conductance values during purging. The same situation applied generally to the behavior of the VOC compounds. Table 4 contains the results for the VOC concentration changes after an initial period of pumping. The concentration levels for the five principal VOCs began to stabilize after pumping an average of 40% (range of 35 to 52%) of a bore volume at ~1 l/min. This range compares favorably to the average percentage bore volumes to stabilization of O_2 (i.e., 44 ± 27%) and conductance (i.e., 44 ± 21%). The VOC concentrations on the stabilization plateau varied within ± 2.2 to 14% relative standard deviation from the means shown in bold in Table 4. This range of variability is well within expectations for repetitive samples from individual wells for VOC concentrations in the range of 10-500 μg/l. The ranges of acceptable limits for reporting VOC concentrations in USEPA Water Supply Performance Evaluation Studies are ± 40 and ± 20% from true values at levels less than 10 μg/l and greater than or equal to 10 μg/l, respectively (Britton, 1992). The stabilization of VOC concentrations during purging at levels within these ranges of analytical performance standards should be more than adequate for most routine monitoring investigations. The stabilization of O_2 or conductance values may not necessarily be predictive of volumes to VOC stabilization. However, in this study all constituents reproducibly stabilized within the same volume range.

Weak linear correlations between higher average stabilized concentration values of the VOCs and higher initial volumes of stabilization were observed in the purging experiment. The correlation coefficients were relatively poor (i.e., r^2 for 1,1DEC = 0.22; 1,1DCA = 0.33; 1,2cisDCE = 0.26; 1,1,1TCA = 0.12; TCE = 0.40). This was due in part to the fact that, in some wells (#'s 21, 23, and 30) with low concentrations of VOCs, negligible changes in concentration were observed during purging. Certainly, well to well variability in VOC concentrations also weakened these correlations. The use of close-fitting dedicated pumps with the intake placed in the middle of the short-screened interval minimized the volume of potentially contaminated water which must be purged at these flow rates prior to sampling. The position of the bladder pump intake and minimal draw-

Table 4. VOC Purging Behavior: Initial Volume of Stabilization, Mean Stabilized Concentrations (C), and Standard Deviation

	Conductance (μS/cm)			Oxygen (mg/l)			1,1DCE			1,1DCA			1,2c-DCE			1,1,1TCA			TCE	
Well #	Vi	C (μS/cm)	Stdev (μS/cm)	Vi	C (mg/l)	Stdev (mg/l)	Vi	C	Stdev	Vi	C	Stdev	Vi	C	Stdev	Vi	C	Stdev	Vi	C	Stdev
15	69	816	15	89	2.1	0.1	41	2.1	(0.05)	41	2.1	(0.32)	93	7.8	(0.08)	93	29.5	(0.8)	41	2.0	(0.3)
16							42	19.6	(1.1)	42	53.7	(2.9)	33	50.8	(2.9)	52	213	(15.7)	52	35.1	(3.7)
17	15	781	8.4	15	3.2	1.0	40	8.9	(1.4)	33	32.5	(1.4)	58	13.9	(0.6)	58	36.9	(1.2)	58	3.9	(0.2)
18	30	732	3.5	55	1.8	0.2	156	36.6	(1.5)	85	87.5	(1.5)	85	144	(1.9)	85	394	(3.6)	85	94.3	(0.4)
19	71	859	12	10	2.4	0.1	+	0.5	—	+	0.5	—	+	0.5	—	+	17.5	(2.1)	+	0.5	—
20	19	824	13	31	0.35	0.2	68	17.8	(2.7)	92	237	(0.2)	92	61.4	(0.6)	29	30.7	(1.9)	+	0.5	—
21							32	7.3	(0.5)	52	18.3	(0.80)	52	12.8	(1.2)	52	78.9	(5.0)	52	14.4	(0.8)
22	68	762	2.5	79	1.2	0.2	4.3	0.87	(0.17)	7.7	2.5	(0.70)	7.7	1.3	(0.22)	50	32.7	(1.7)	50	0.94	(0.15)
23	17	745	1.6	83	3.9	0.7	3.4	0.93	(0.10)	21	3.3	(0.20)	6.1	1.1	(0.30)	6.1	23.4	(0.8)	6.1	1.3	(0.12)
24	41	733	4.4	41	3.8	0.1	2.6	0.5	—	7.8	0.5	—	7.8	1.0	—	2.1	6.4	(0.3)	2.1	1.1	(0.1)
27	37	728	3.8	22	4.7	1.0	92	17.3	(3.9)	22	39.5	(1.8)	22	45.4	(1.6)	32	138	(6.7)	32	43.7	(1.95)
28	62	671	3.7	27	2.5	0.2	110	29.9	(3.2)	15	99.7	(3.0)	15	90.1	(6.5)	1.0	155	(7.8)	1.0	53.2	(1.1)
29	38	791	3.6	38	3.0	0.1	+	—	—	+	—	—	+	—	—	9.6	5.5	(0.3)	9.6	1.0	(0.1)
30	60	797	5.8	37	4.1	0.1	28	5.5	(0.7)	9.3	11.0	(0.6)	19	10.2	(1.0)	28	64.7	(3.3)	28	13.4	(0.6)

Vi = % bore volume at which stabilization began.
C = Mean concentration (μg/l) (except where otherwise indicated) on stabilization plateau.
Stdev = Standard deviation (μg/l) (except where otherwise indicated) on stabilization plateau.
+ = No significant delay to stable or nondetectable concentration.
— = Concentration values too low or intermittent to estimate mean or standard deviation.

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down during pumping provide the basis for consistent measurements of both the purging indicator parameters and VOCs.

Documentation of the behavior of the indicator parameters during purging of individual wells provides a body of data with which the consistency of field sampling procedures can be judged over time. They should be considered as part of QA/QC guidelines in monitoring efforts. Under similar hydrogeologic conditions, a two person crew could easily sample 10 or more wells per day following the suggested low flow-rate well-purging method. In the course of a day of sampling, less than 500 l of potentially contaminated water would need to be handled by the field crew. This purging method has distinct advantages for long-term monitoring efforts in terms of cost and the minimization of volumes of purged water for treatment or disposal.

VOC Purging Criteria

Recommended criteria in the literature for the stabilization of chemical constituents during purging vary. Most have centered on the variability of indicator parameters, for example, O_2, conductance, temperature, and pH (Gibb et al., 1981; Barcelona et al., 1985) or the maximum rate of change for indicator parameter and VOC concentrations (Gibs and Imbrigiotta, 1990) over a specified volume. The choice of the level of acceptable variability over the appropriate flow rate and volume (i.e., bore volume, screen volume, sandpack volume, etc.) on the purging plateau should be carefully evaluated for the hydrogeologic setting, monitoring well design, and hydraulic performance.

Even when we applied the apparently stringent equilibration variability criteria suggested by Gibs and Imbrigiotta to the purging data presented in this study, a fraction of a bore volume (i.e., < 50%) would be sufficient to achieve stabilization. From the present observations, approximately $\pm$ 0.2 mg/l O_2 and $\pm$ 10 μS/cm conductance Ω^{-1} over one-half bore volume after the initial volume of stabilization, would be considered reasonable field criteria for the indicator parameters (since pH and T were relatively insensitive to purging). This procedure would be expected to minimize the purge value requirement well below that called for by recommendations of three to five bore volumes (Gibb et al., 1981).

Ideally, one could take sequential samples during purging for VOC determinations from a "typical" well at a site. This would establish a more site-specific correspondence between the easily measured indicator parameters and the behavior of VOCs during sampling. Low flow-rate purging with dedicated bladder pumps or similar devices would certainly avoid the excessive variability and perhaps failure to achieve stable values reported in high flow rate pumping studies (Clarke and Baxter, 1989; Pionke and Urban, 1987; Gibs and Imbriogiotta, 1990). Gibs and Imbrigiotta pumped their wells during purging at rates of 4 to 25 l/min. In fact, in three of their six cases in which "unstable" concentration values for two or more compounds were observed during purging, the entrance velocity through the screen exceeded the optimum screen velocity for production wells of the same diameter (assuming 50% blockage of the open area of the screen). At low flow rates, one avoids: pumping excessive volumes of water, further well development, excess turbidity, and well damage which can lead to systematic error (i.e., bias) in chemical constituent determinations.

Monitoring Well-Purging Hydraulics

The extension of the above results to other hydrogeologic settings, well designs, pumping rates, etc., depends on considerations of the hydraulics of the monitoring wells and the distribution of chemical constituents adjacent to the screen. Empirical observations of volumetric purging behavior of VOCs reported in this study and by Gibs and Imbrigiotta (1990) did not correlate well with the concentration levels of the constituents, hydraulic conductivity, transmissivity, or the critical hydraulic residence times calculated by Schafer's (1978) method.

Robbins (1989) and Robbins and Martin-Hayden (1991) developed a treatment of the purging behavior of wells for VOCs which can be applied to the study results. Their mass-averaging model expression for purging is shown below in equation (1).

$$C_w = C_f + (C_o - C_f)\exp(-V_e/V_w) \qquad (1)$$

where C_w = concentration pumped; C_f = concentration at stabilization; C_o = initial concentration ($C_o = C_w$); V_e = cumulative volume pumped during purging; and V_w = well volume. This equation was used to determine the best-fit between the purging observations in this study with the model prediction for different water volume values for V_w (i.e., $V = V_{BV}$, $V_{sp/sc}$ or V_{sc}). The borehole volume V_{BV} was assumed to include water in the casing, screen, and sandpack. $V_{sp/sc}$ included the volume in the screened interval and the sandpack (i.e., the borehole around the screen corrected for porosity). V_{sc} included the volume in the screened interval minus that occupied by the pump.

The predicted concentrations C_w, as a function of the volume pumped for each relevant "storage" volume V_w, are shown in Figures 6(a), (b), (c), (d), (e), and (f) for O_2, conductance, and 1,1,1 TCA in wells 18 and 24. The plots for these typical wells show that the best-fit of the observed concentrations to those predicted by the mass-averaging equation were calculated when the screen volume was used for V_w.

In general, conductance observations most closely matched predictions. This is probably due to the fact that conductance best reflects major ion chemistry which is less affected by either volatilization or small-scale heterogeneity in subsurface formations than oxygen or volatile constituents. Table 5 contains the results for all of the best-fit linear regressions of observations versus predicted values for the selected constituents which consistently showed appreciable purging variability in all wells in the study. Out of 91 total cases, 47 showed both detectable levels and significant concentration variations during purging which permitted meaningful comparison. Of these cases, 34 showed linear correlation coefficients (r^2) above 0.5. Twenty-seven of these were observed when $V_w = V_{sc}$ and eight when $V_w = V_{sp/sc}$. In only one case, the best-fit correlation coefficient exceeded 0.5 for $V_w = V_{BV}$. The higher general correlation between the

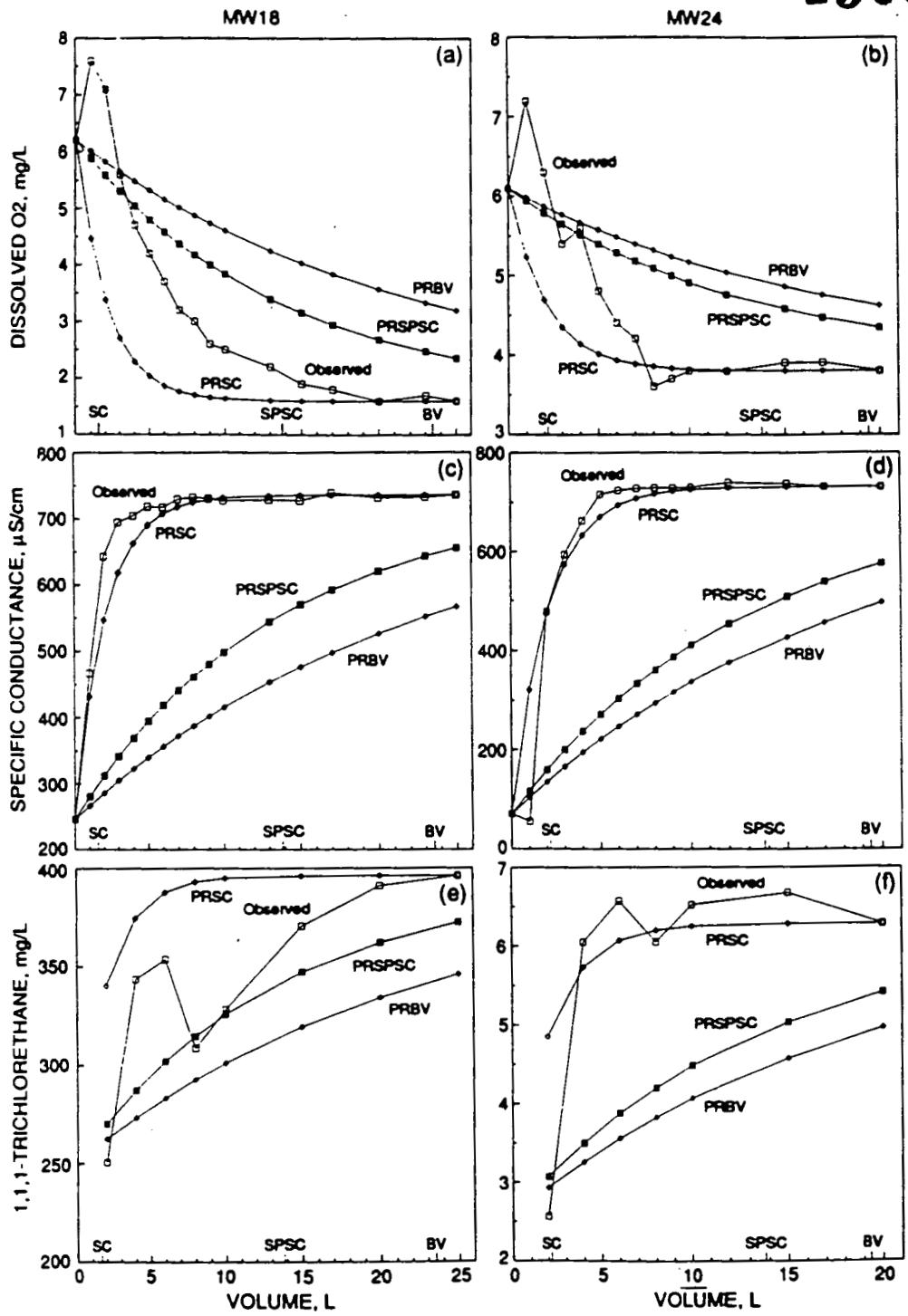

Fig. 6. Purging observations and mass-averaging equation predictions for dissolved O_2, specific conductance, and 1,1,1-trichloroethane vs. volume pumped for wells 18 and 24. Observations are denoted by open square symbols (□); PRBV = borehole volume predicted value; PRSPSC = sandpack/screen volume predicted value; PRSC = screen volume predicted value.

observed values and those predicted by $V_w = V_{sc}$ or $V_{sp/sc}$ may reflect the fact that minimal drawdown during purging effectively isolates the stored volume in the casing above the screen from the pump intake. The use of relatively close-fitting dedicated bladder pumps further minimized the pathway by which "stored" water could move into the screen. Maltby and Unwin (1992) have previously observed a degree of isolation of stored water in the casing above the screen when pumping slowly from the screened interval. "Fresh" ground water then may move into the screen nearly at the onset of pumping.

This encouraging agreement does not constitute a predictive relation for the empirical results one might expect under other hydrogeologic conditions. Robbins and Martin-Hayden have pointed out that the length of the screen and the concentration distribution adjacent to the screen exert the principal controls on the bias introduced into purging and sampling results due to mass averaging. Attempts were

Table 5. Best-Fit Volume and Correlation Coefficients for Predicted and Observed Purging Behavior of Selected Chemical Constituents

Well	*Cond*	*O_2*	*1,1,1TCA*
15	SC* (0.1)**	SC (0.86)	SC (0.1)
17	SC (0.75)	SC (0.1)	SC (0.13)
18	SC (0.95)	SC (0.65)	SPSC, SC (0.69, 0.63)
19	SC (0.71)	SC (0.27)	SPSC (0.71)
20	SC (0.92)	SPSC (0.70)	SC (<0.1)
21			SC (0.62)
22	SC (0.85)	SPSC, SC (0.90, 0.54)	SC (0.28)
23	SC (0.94)	SPSC, SC (<0.1)	SPSC (0.53)
24	SC (0.92)	SC (0.67)	SC (0.90)
27	SC (0.94)		SC (0.79)
28	BV, SPSC; SC (0.94; 0.84)	SC (0.46)	SC (0.51)
29	SC (0.91)	SC (0.83)	
30	SC (0.81)	SC (0.23)	SPSC (0.32)

* = Volume V_w in mass-averaging equation [Eq. (1)].
** = r^2, linear best-fit correlation coefficient.
SC = Screen volume.
SPSC = Sand/pack/screen volume.
BV = Casing, screen, and sandpack volume.

made to linearize their equation to derive a "well volume" applicable to each parameter fitted to the observations.

Equation (1) was transformed to:

$$\log\left(\left|\frac{C_w - C_f}{C_o - C_f}\right|\right) = \frac{-V_e}{2.3\,V_w} \qquad (2)$$

The log of the absolute value of the concentration ratio was then plotted versus the cumulative volume pumped (V_e) where the slope was $-(1/2.3\,V_w)$. These calculations did not yield reasonable linear relationships by which consistent V_w values could be estimated within ± 100% even for the conductance values. Further work is clearly needed to better integrate vertical gradients in chemical constituent concentrations and monitoring well hydraulics with purging behavior. Care should be taken to avoid screening monitoring wells across variably permeable formations or those with strong vertical chemical concentration gradients (Gibs et al., 1993; Powell and Puls, 1993).

Conclusions

Consistent well purging and sampling procedures must be carefully chosen to meet the purposes of investigations, the hydrogeologic setting, and the hydraulic performance of sampling points. Proper well development to remove fines created during drilling is a necessary first step to avoid excess turbidity and particulate artifacts. Compressed air development, followed by pumping of oxygenated water appears to be a viable method for the development of small diameter wells in transmissive formations.

Low flow-rate pumping to purge and sample short-screened wells, with dedicated bladder pumps set in the screened interval, causes negligible drawdown. It further permits the in-line observation of stabilization of indicator parameters as a function of volume pumped. At flow rates of ~ 1 l/min, oxygen, conductance, and VOC levels stabilized consistently after pumping less than one-half of a bore volume. Stabilization within ± 0.2 mg-O_2/l and ± 10 μS/cm specific conductance (for wells with conductances < 1,000 μS/cm) over successive bore volumes represents reasonable, initial, field criteria for judging purging effectiveness. Observations of indicator parameter stabilization during low flow-rate pumping represent a consistent basis for purging prior to sampling for volatile organic compounds which may not require purging three to five bore volumes. This purging procedure is reasonably consistent with those predicted due to the hydraulic effects of mass-averaging. VOC concentrations stabilized within 15% of annual mean values when these criteria have been applied.

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