Journal of Hydrology 266 (2002) 162–174

www.elsevier.com/locate/jhydrol

Lag times of bank filtration at a well field, Cincinnati, Ohio, USA

R.A. Sheets[a,*], R.A. Darner[a], B.L. Whitteberry[b]

[a]*US Geological Survey, 6480 Doubletree Avenue, Columbus, OH 43229, USA*
[b]*Cincinnati Water Works, 5651 Kellogg Avenue, Cincinnati, OH 45228, USA*

Received 13 July 2001; revised 7 August 2001; accepted 1 September 2001

Abstract

Wells placed next to surface-water bodies to induce infiltration have come under scrutiny because of the presence of the potential pathogens in surface water. Removal of pathogens and other contaminants by bank filtration is assumed, but regulatory agencies question the effectiveness of this process. To investigate transport processes of biological constituents, advective groundwater traveltimes to production wells under the influence of surface water need to be established first to determine appropriate water-quality sampling schedules.

This paper presents the results of a study of bank filtration at a well field in southwestern Ohio. Field parameters such as water level, specific conductance, and water temperature were measured at least hourly at a streamflow gaging station and at five monitoring wells each at two separate sites, corresponding to two nearby production wells. Water-quality samples also were collected in all wells and the streamflow gaging station.

Specific conductance is directly related to concentration of chloride, a chemically conservative constituent. Cross-correlation methods were used to determine the average traveltime from the river to the monitoring wells. Traveltimes based on specific conductance ranged from approximately 20 h to 10 days at one site and 5 days to 3 months at the other site. Calculated groundwater flow velocities ranged from 2.1×10^{-3} to 6.0×10^{-3} cm/s and 3.5×10^{-4} to 7.1×10^{-4} cm/s at the two sites. Data collected when a production well is continuously pumping reveal shorter and more consistent traveltimes than when the same well is pumped intermittently. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Bank filtration; Specific conductance; Temperature; Statistical analysis; Traveltime

1. Introduction

Bacteria, viruses, and pathogenic protozoa such as *Giardia lamblia* and *Cryptosporidium parvum* in surface waters can degrade groundwater quality in areas of induced infiltration and could affect the health of people ingesting these groundwaters. With the passage of the Surface Water Treatment Rule in 1986 and the subsequent Interim Enhanced Surface Water Treatment Rule (US Environmental Protection Agency, 1998), the United States' water-supply industry was introduced to the concept of 'groundwater under the direct influence' (GWUDI) of surface water. Groundwater sources that are deemed GWUDI are at risk for being contaminated with surface-water-borne pathogens (specifically disinfection-resistant pathogenic protozoa). Many supply wells are installed adjacent to surface-water bodies to increase production through induced infiltration. In areas of induced infiltration, bank (or natural) filtration by riverbed, riverbank, or aquifer material commonly is

---

[*] Corresponding author. Tel.: +1-614-430-7710; fax: +1-614-430-7777.
E-mail address: rasheets@usgs.gov (R.A. Sheets).

PII: S0022-1694(02)00164-6

assumed to impede transport of biological and chemical pollutants to the groundwater supply (Bourg and Bertin, 1993; Macler, 1995). Fate and transport of chemical constituents, such as nitrate and herbicides, from a surface-water source to pumping wells has been examined (e.g. Grischek et al., 1998; Verstraeten et al., 1999). The effect of the riverbed and aquifer materials in providing natural filtration of biological contaminants through a combination of filtration, adsorption, predation, natural die-off, and dilution also has been examined through column and field studies (McDowell-Boyer et al., 1986; Gerba et al., 1991; Harvey, 1997).

Until recently, if a production-well facility was declared GWUDI, no mechanism was available to assign ‘credit’ for bank filtration; the facility was required to treat the source as surface water. With the advent of the Long Term (2) Enhanced Surface Water Treatment Rule (primarily to address *Cryptosporidium parvum*), facilities may obtain log-reduction credit for the bank-filtration process. However, there is a scarcity of data that show quantification of the log removal. The bank-filtration process is not easily measurable owing to the lack of one or more easily measured surrogates of the pathogens and the lack of control over the variability of hydrologic conditions (e.g. infiltration rates or groundwater flow rates).

This paper presents some of the results of field-based research at a large public-supply well field adjacent to a river in southwestern Ohio, USA, and describes the relations between easily measurable river-water characteristics and several monitoring wells placed between the river and two production (water-supply) wells at the well field. Lag times (i.e. the difference between a marked physicochemical change in the river water and a subsequent change in well water) are calculated for temperature and specific conductance, and the latter used for estimates of average advective groundwater traveltimes. These lag times can form the basis for further investigations into the processes of pathogen transport.

2. Site description and background

The Charles M. Bolton well field is north of Cincinnati, Ohio (Fig. 1), within the Miami Valley Buried Aquifer (http://www.epa.gov/safewater/swp/ssa/reg5.html). The well field is adjacent to the Great Miami River and consists of 10 production wells, which supply an average of approximately 57–61 million liters per day (Ml/d) to residents of northern Cincinnati, Ohio, although the total maximum sustained yield is estimated to be in excess of 136 Ml/d. At the well field, the Great Miami River drains an area of 9505 km^2 composed of predominantly agricultural areas in the upstream reaches of tributaries and urban areas (for example, the City of Dayton, OH) near the main trunk of the Great Miami River.

The Miami Valley Buried Aquifer in this area consists of highly permeable sand-and-gravel outwash and meltwater deposits with relatively small amounts of clay. The aquifer is underlain and laterally bounded by Ordovician bedrock consisting of poorly permeable interbedded limestone and shale, whose groundwater yields are low. In the uplands, the bedrock generally is overlain by glacial till, which also is poorly permeable. Depth to bedrock in the center of the valley is 46–61 m below land surface. Hydraulic conductivity of the aquifer in this area, based on aquifer tests, ranges from 0.11 to 0.18 cm/s (Dove, 1961; Smith, 1962).

Conceptually, groundwater flow to pumping wells placed next to the river is from induced infiltration and from regional, down-valley flow. Two sites (sites 1 and 8), corresponding to production wells, were chosen for this study (Fig. 1): site 1 is at the northernmost edge of the well field with minimal influence from other pumping wells within the well field; site 8 is in the center of the well field. Fig. 2 is a generalized cross section through one of the production wells, with approximate locations of monitoring wells and the conceptualized groundwater flow during pumping. The wells were constructed to intercept potential groundwater flowpaths from the Great Miami River to the production wells. Dedicated data sondes and pumps in the wells allow measurements of water-quality characteristics during a wide range of river flow (Gollnitz et al., 2000). A numerical groundwater flow model also was developed to help clarify stream–groundwater relations (Sheets et al., 2000).

Because of the high transmissivity of the Miami Valley Buried Aquifer in the area, many investigations have been done in and around the Bolton well

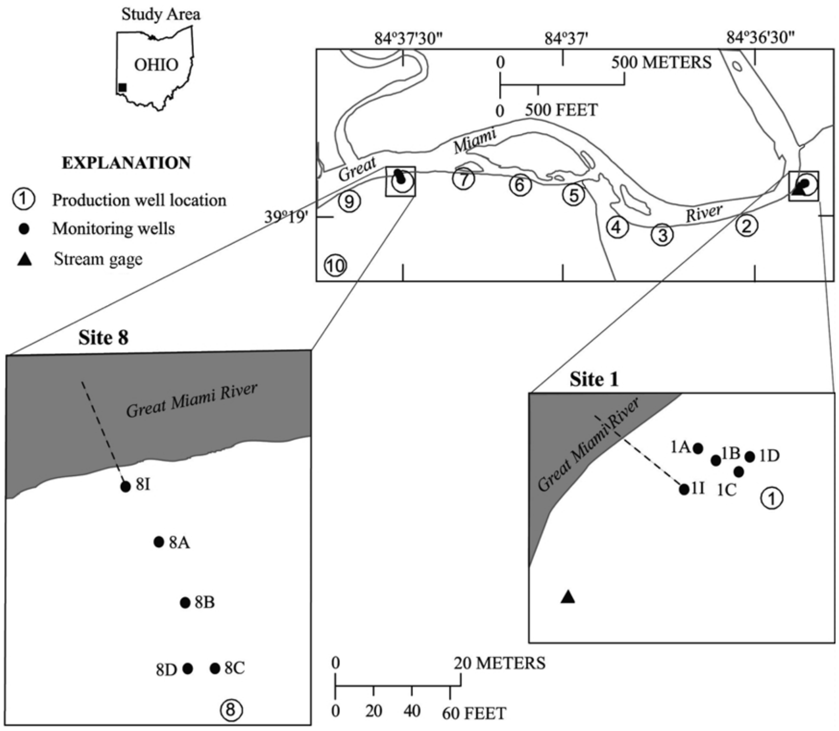

Fig. 1. Location of Charles M. Bolton well field and monitoring wells.

field. Such investigations have concentrated on infiltration rates, because of the interaction of the Great Miami River and the aquifer. Dove (1961) and Walton et al. (1967) used flow-net analyses to estimate infiltration rates from the Great Miami River to a well field developed in the buried-valley aquifer, approximately 3.2 km downstream from the Bolton well field. Assuming uniform infiltration rates across the riverbed and an average width of the river, they applied their methods when the average

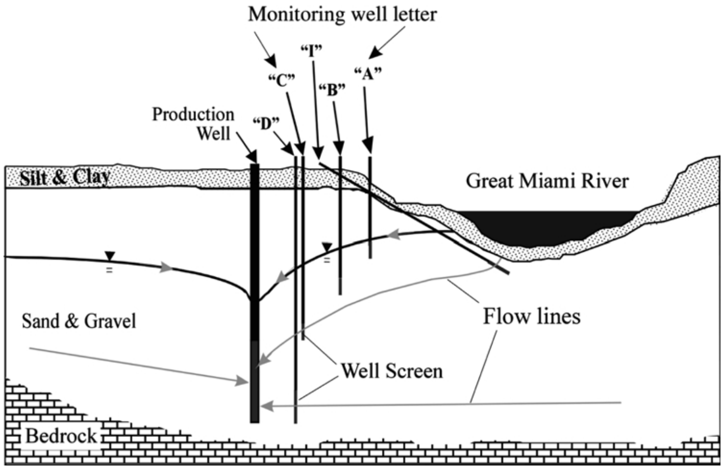

Fig. 2. Generalized cross section showing conceptualized flowpaths (vertical distance approximately 150 m and horizontal distance approximately 800 m; vertical exaggeration × 2).

temperature of the Great Miami River was about 28 °C. Their methods yielded averages of 0.737 and 0.516 m^3/d per square meter of riverbed per meter of drawdown ((m/d)/m), respectively. When accounting for variations of river channel geometry, Walton's (1967) estimates ranged from 0.123 to 1.28 (m/d)/m. Walton et al. (1967) also extended his investigation to estimation of induced infiltration rates based on changing river gage heights and river temperature. In an exploratory study for the Bolton well field, Smith (1962) used aquifer-test results from a site directly across the Great Miami River to determine an average infiltration rate (from the river) of approximately 1.15 (m/d)/m. All these aforementioned infiltration rates indicate that the river could provide much of the recharge to wells placed next to the river. For reference, the mean annual streamflow in the Great Miami River near the Bolton well field is 94.99 m^3/s (8328 Ml/d; Great Miami River at Hamilton, 1927–99, Shindel et al., 2000). The lowest daily mean streamflow during the period of record was 4.39 m^3/s (379 Ml/d; September 27, 1941).

3. Methods

In our study, rotosonic drilling methods (Wright and Cunningham, 1994) were used to complete four vertical monitoring wells at each production-well site (well 1 and 8, Fig. 1), at various depths. Each borehole was 20.3 cm in diameter, and intact 10.2 cm cores were collected from each vertical borehole inside plastic sleeves. A geologist on site described each intact core. Selected sections of the cores were distributed to Miami University (Ohio) and the USGS Branch of Regional Research Laboratory for Bacteria-Contaminant Interactions, Boulder, Colorado. Miami University performed column experiments to examine transport characteristics of bacteria in cores that remained largely undisturbed from the drilling (Sun et al., 2000). The Boulder laboratory repacked the core material from the monitoring boreholes and examined the characteristics of transport of *Cryptosporidium parvum* oocysts (Metge et al., 2000). An inclined monitoring well was completed at each of the two sites, also with rotosonic drilling methods. The inclined wells were placed so that the screened interval was approximately 2–4 m beneath the Great Miami River; at sites 1 and 8, the boreholes were drilled approximately 20 and 30° from horizontal, respectively (well labeled 'I', Fig. 2). Loose core material was collected from each inclined borehole.

After collection of core material, 0.61 m long, 10.2 cm diameter PVC well screens and well casing were placed into the drill rods, which were pulled back to allow aquifer material to collapse around the screen and casing; screw joints were used in construction. The vertical monitoring wells were designated A through D, from shallowest to deepest (Fig. 2). Monitor wells A through C were placed in more or less regular intervals from the approximate river-bottom elevation to the top of the production-well screen. Monitor wells D are placed near the bottom of each production well screen. Production well 1 is completed from 17.4 to 26.5 m below land surface, and production well 8 from 27.4 to 56.7 m below land surface; therefore, monitoring wells at site 1 are much shallower (closer to the river bottom) than at site 8.

Each vertical and inclined monitoring well was instrumented with a multi-parameter data sonde, which continuously (at 1 h intervals) measured temperature, specific conductance, dissolved oxygen, pH (hereafter referred to as 'field parameters'), and water level. Data sondes in the inclined wells and well 1A were also instrumented with optical turbidity probes; a chlorophyll probe also was installed in well 1I (Fig. 1). A dedicated low-volume pump also was installed in each well below the data sonde to collect groundwater samples. A streamflow gaging station established at production well 1 continuously (at half-hour intervals) monitored temperature, specific conductance, turbidity, dissolved oxygen, pH, chlorophyll and river gage height (Fig. 1). Each data sonde was serviced about every 2 weeks and recalibrated as needed. Data collected were downloaded to a laptop computer and, after data-quality checks, were input to the US Geological Survey (USGS) database.

Water-quality samples were collected with the dedicated low-volume pumps. Field parameters were measured as a minimum of three to five volumes of tubing was purged from the well. Samples were collected after purging criteria were met and field parameters had stabilized. The USGS collected additional quality-assurance/quality-control samples, which were submitted to the USGS National Water Quality Laboratory in Denver, Colorado and analyzed as a quality-assurance measure for laboratories and data used in the study.

For each of the monitoring wells, the statistical procedure ARIMA (autoregressive integrated moving average; Brocklebank and Dickey, 1986) was used to quantify the lag times of temperature and specific conductance and the statistical significance of the lag time, by means of cross-correlation of the variables. ARIMA involves developing a regression model in which a time series (for example, well 1I temperature data) is the dependent variable; a related time series (river temperature data) is the independent or predictor variable. A regression coefficient describes how well the dependent time correlates with the independent time series as the dependent series is shifted backward along the independent series. Although not as robust a procedure but yielding similar results, the dependent variable time series can be translated backward in time along the independent time series and a simple linear regression coefficient can be calculated. The most significant lag is recognized as the highest regression coefficient. A regression coefficient of 1.0 indicates that the two series are perfectly correlated, just offset in time.

4. Results of continuous monitoring

Relations between the Great Miami River and the underlying aquifer at the well field, as examined through continuous monitoring of water levels and field parameters, may lend insight into transport of potential pathogens to these public supply wells. Section 5 illustrates data collected from the gaging station on the Great Miami River and monitoring wells at sites 1 and 8.

Water levels in the monitoring wells reflect pumping in the production well immediately adjacent to the monitoring-well cluster and water levels in the Great Miami River (Fig. 3). To a lesser extent, pumping from nearby production wells may have affected water levels in the monitoring wells, especially at site 8. Production well 1 (PW-1) was intermittently pumped, on an as-needed basis for production, until August 23, 2000, after which it was continuously pumped at a rate of approximately 15 Ml/d (except for very brief periods of equipment malfunction). Production well 8 (PW-8) was intermittently pumped (approximately 13.6 Ml/d) during the entire monitoring period.

Analyses of water levels in the monitoring wells at site 1 indicate that, during periods of sustained pumping, the Great Miami River in the vicinity of the production wells is classified as a losing river. Water levels in successively deeper monitoring wells indicate a distinct and consistent downward gradient toward the production well. If a particular production well was turned off for a period of at least 2 days (and the streamflow was not affected by a rainfall event), the Great Miami River reverted to a gaining river. During nonpumping intervals, water levels in monitoring wells adjacent to the production well generally were higher with increasing depth, indicating that groundwater in the deeper parts of the aquifer was eventually discharging to the river. During some nonpumping intervals at the production well immediately adjacent to the monitoring wells, water levels in the deeper wells were lower than those in shallower wells ($\cong 5$ cm), an indication that pumping from other wells in the well field affects the natural hydraulic gradients and induces infiltration of river water into the aquifer.

Temperature data from the river and the monitoring wells at both sites (Fig. 4) show the sites are similar in some respects but also differ greatly in other respects in response to river temperature. All monitoring wells, except the deepest well at each site (1D and 8D), respond to seasonal fluctuations in river temperature; however, the maximum and minimum temperatures at site 8 wells can be 3–10° different than the maximum and minimum river temperatures, whereas well temperatures at site 1 are much closer to river temperatures. The similarity between thermographs of the river and shallow monitor wells at site 1 suggest more rapid infiltration of river water at site 1 than at site 8. The lag time between a surface-water temperature and groundwater temperature in a monitoring well is best illustrated with site 8, where the river-water temperature reaches a minimum at about mid-January 2000 and temperatures in well 8B reach a minimum at about the beginning of April 2000—a lag time of approximately 75 days. A cursory analysis of well data for site 1 seems to indicate that water

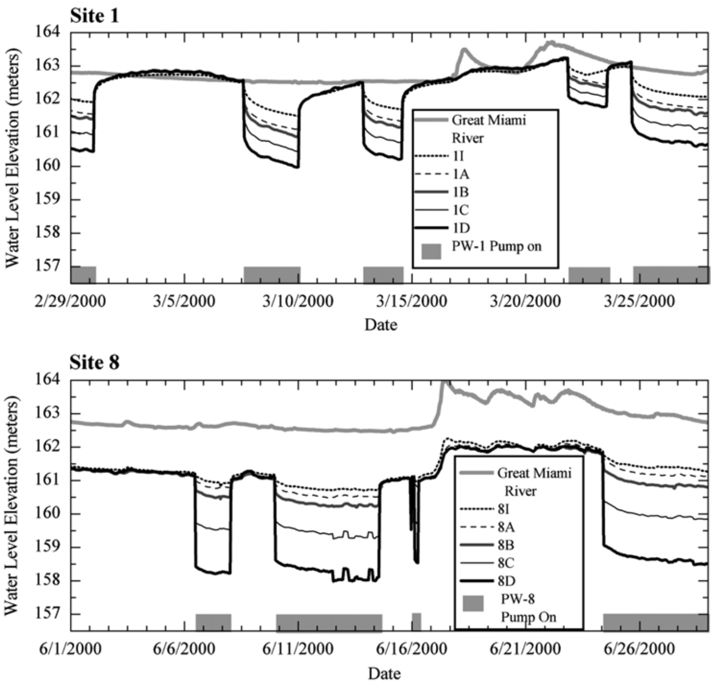

Fig. 3. Water levels in the Great Miami River and in monitoring wells at site 1 and site 8.

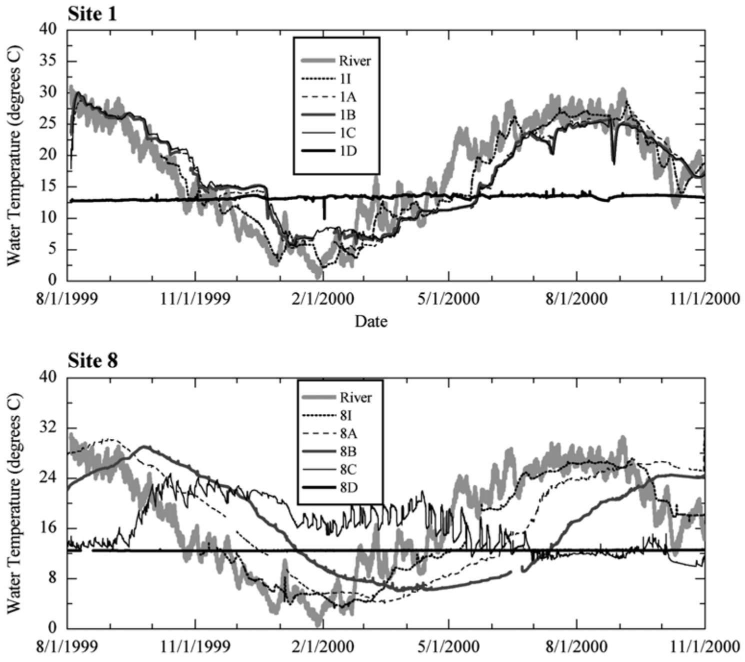

Fig. 4. Thermographs from the Great Miami River and monitoring wells at site 1 and site 8.

temperatures in the monitoring wells more closely mimic surface-water temperatures after August 2000, at which time production well 1 was pumped continuously, instead of intermittently.

The between-site difference in groundwater response to temperatures probably is due to a variety of factors, the most important being distance to monitoring wells from the river bottom and permeability of riverbed sediments at each site. The depths to the monitoring wells from the river bottom are approximately 1.5, 4.6, 7.6, 12, and 20 m at 1I, 1A, 1B, 1C, and 1D, respectively, and 1.5, 6.1, 12, 24, and 52 m to 8I, 8A, 8B, 8C and 8D, respectively. Site 1 is at a cut bank of the Great Miami River, where glacially derived sediments are deeply incised and little fine-grained alluvial sediments is deposited; site 8 is near a riffle and pool, where alluvial sediments accumulate and deep incision of more permeable glacial sediments rarely occurs. A riverbed-permeability survey using methods by Lee (1977), combined with a surface electromagnetic survey (to distinguish between fine-grained and coarse-grained sediments), indicates that riverbed permeability may decrease slightly from site 1 to site 8. Previous data also indicate that site 1 is the more susceptible to hydraulic influences from the Great Miami River, possibly because of screen depth, riverbed material, water depth of the Great Miami River, as well as other factors.

The deepest monitoring wells at each site (1D, 8D) are screened near the bottom of the nearby production-well screen. The absence of response to river temperature fluctuations at the deepest monitoring wells, even though the monitoring well completed above it responds readily, indicates that pumping from the nearby production well captures most of the water near the top of the screen from the nearby water table (ultimately the Great Miami River) and most of the water near the bottom of the screen is captured from more of a regional groundwater flowpath.

Specific conductance measurements made in the Great Miami River and in monitoring wells at site 1 are plotted in Fig. 5. With the exception of well 1D, specific conductance fluctuations in the wells mimic specific conductance and gage-height fluctuations in the Great Miami River, although the responses of each successively deeper well are muted with respect to specific conductance of the river. Although the specific conductance in 1D is nearly constant, slight decreases over time may indicate that water from the river eventually reaches well 1D. On at least 18 occasions during data collection, specific conductance in each of the monitoring wells lags specific conductance ‘troughs’ in the river from 1 day to nearly 2 weeks. Changes in specific conductance in monitoring wells at site 8 are more muted, and lag times are not as evident.

Continuous measurements of pH in the Great Miami River indicate wide fluctuation (7.5–9.2; median = 8.4), with occasional rapid decreases in response to increased gage height. Much less variability was measured in the monitoring wells, and that variability decreased with depth. The pH in water for wells 1I and 8I was very similar and ranged from 7.1 to 8.2 (median = 7.6), whereas the range for 1D and 8D was from 6.9 to 7.6 (median = 7.3). Except for the inclined wells, completed near the river bottom, no relation was evident between pH fluctuations in the river and in the aquifer; only a few times during marked decreases in pH in the river did the shallowest wells seem to respond. The pH in groundwater at the site probably is buffered somewhat by the large component of calcium carbonate sediment in the aquifer.

Continuous turbidity measurements made in the inclined wells generally showed very little response to changes in turbidity in the river. Continuous turbidity measurements made at well 8I indicated some response to the river but only during large events (gage height increases), an indication that localized scouring of the riverbed may have nearly intercepted the screened interval of the well. Periodic measurements of turbidity were made in the other monitoring wells, and higher turbidity often was measured within a few hours of the onset of a rise in river gage height. These measurements of high turbidity may be a result of a combination of rapid increase in hydraulic head, aquifer stratigraphy, and well construction. A rapid increase in hydraulic head may mobilize clay- and silt-sized particles immediately surrounding a monitoring well, particles that otherwise would not enter the well. For instance, at site 8, turbidity readings for well 8D frequently were higher than for monitoring wells completed shallower and closer to the river.

Dissolved oxygen (DO) concentrations in the river ranged from 2.47 to 19.6 mg/l, with a median of

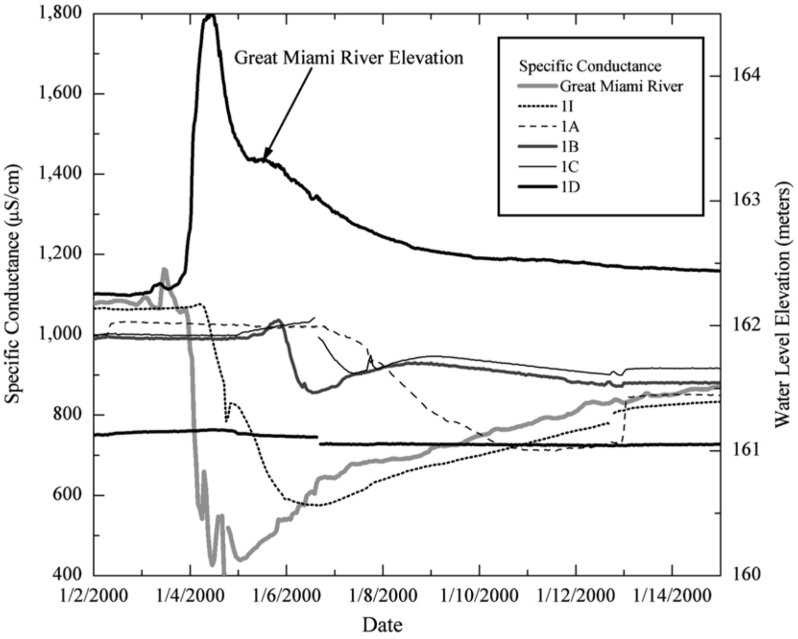

Fig. 5. Response of specific conductance in the Great Miami River and in monitoring wells at site 1.

10.8 mg/l. At well 1I, DO generally was very low (median 0.1 mg/l), but during one approximately 2 m gage height increase, it spiked at 9.4 mg/l. Median DO also was low at well 8I (0 mg/l), but it spiked more often and at higher concentrations than at well 1I, probably because of scouring of the riverbed. With either inclined well, very few gage-height increases indicating a direct response of well DO to river DO; this muting or absence of response may indicate an interaction of DO with organic material in the riverbed or hyporheic zone. At the deep monitoring wells at each site, median DO concentrations were equal to or less than 0.1 mg/l.

Chlorophyll was measured continuously in the Great Miami River and in well 1I. Although chlorophyll measurements reached nearly 700 μg/l in the river, chlorophyll readings in well 1I always were very low (< 8 μg/l) and did not correlate with those of the river.

5. Lag-time analyses using temperature and specific conductance

The temperature profiles for monitoring wells at sites 1 and 8 (Fig. 3) indicate that temperature pattern in each of the wells lags in time from the temperature pattern in the river. The results of the lag-time analyses for sites 1 and 8 temperature data are shown in Fig. 6. Except for wells 1D and 8D, the lag regression coefficients are high (> 0.7) indicating that temperatures in the wells are temporally related to temperatures in the river. Records for wells 1D and 8D show no indication that temperatures from the river are transmitted to that depth in the aquifer. Generally, lag times are longer with increasing depth in the aquifer; well 1A is anomalous, but the screen at 1A is actually lateral to the riverbank at site 1, where engineering controls for the cut bank (rip–rap) may be impeding lateral flow and affecting the lag time. The lag times for wells at site 1 are significantly shorter than those for site 8; thus, either the processes for temperature transmittal through the river bottom and to the wells differ between sites 1 and 8 or the processes are the same but the physical properties of the riverbed and aquifer materials are different.

The processes may include advective groundwater flow and conduction or convection of temperature through the glacial/alluvial material. The temperature results also may be affected by antecedent conditions

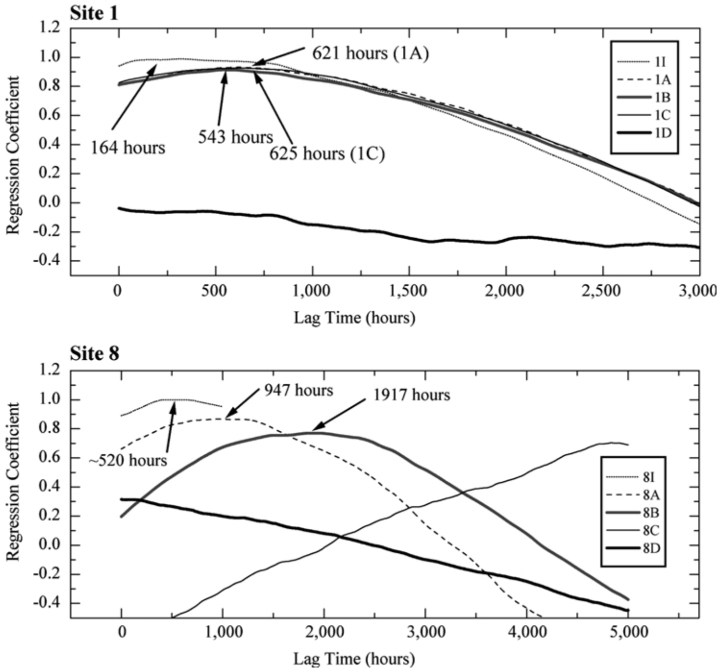

Fig. 6. Lag-time plots based on temperature for monitoring wells at site 1 and site 8.

that would be difficult to quantify. Riverbed or aquifer permeability is a major control on advective groundwater flow. Water-level response, riverbed morphology, and riverbed measurements indicate that riverbed and aquifer permeability likely is higher at site 1. Because advective groundwater flow is only part of the transport mechanism for temperature, and the other processes (i.e. conduction and mixing) would serve only to increase the traveltime of temperatures, the actual advective groundwater flow likely would travel to the well faster than the temperature front.

Specific conductance was the other continuously measured field parameter that was useful for estimating advective groundwater flow traveltimes through the river bottom and aquifer to the monitoring wells. Although chemical processes in the riverbed or aquifer may affect specific conductance, advective flow would be the dominant process for transport of common ions (reflected by specific conductance) in the aquifer, if specific conductance can be correlated with a conservative chemical constituent. Specific conductance of river water is highly correlated with chloride (Fig. 7), which generally is thought to be chemically conservative (Hem, 1985). Therefore, lag times based on specific conductance should be relatively good estimates of advective groundwater flow traveltimes from the river to the various wells.

Before specific conductance lag times from the river to the monitoring wells are discussed, the relation between gage height/discharge in the river and specific conductance in the river should be discussed. The rise of stage propagates downstream at a rate that exceeds the average water velocity in a channel (Walling and Webb, 1980), thereby causing a time delay between the observed discharge maximum (peak gage height) and a concentration minimum (specific conductance trough). ARIMA was used to evaluate the average time lag between the peak stage and specific conductance; an average time delay of 7.5–8 h was observed (Fig. 8). This time delay becomes an important factor if peak gage height is to be used for calculation of time delay of contaminant transport from the river to the production wells.

Lag-time plots of specific conductance from the Great Miami River to each of the monitoring wells at each site are shown in Fig. 9. The point at which the correlation coefficient is highest can be considered the

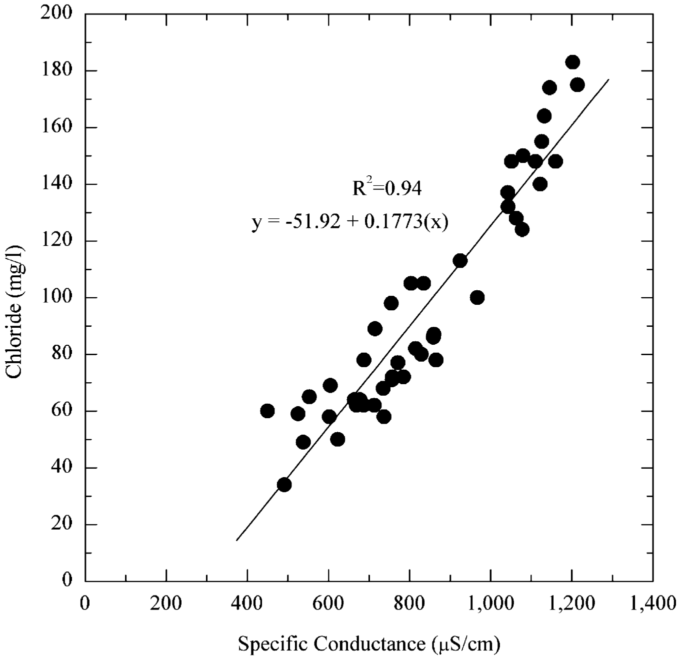

Fig. 7. Relation between specific conductance and chloride concentration in the Great Miami River.

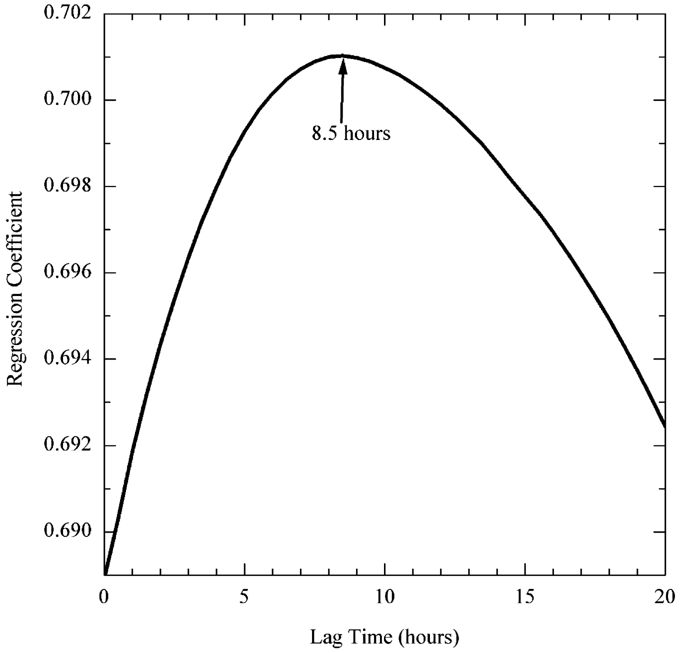

Fig. 8. Specific conductance lag from peak gage height in the Great Miami River.

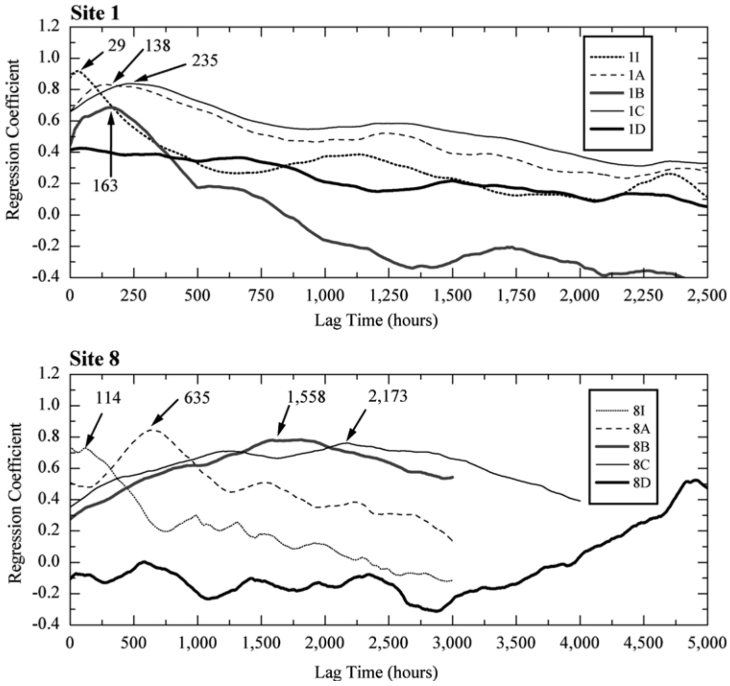

Fig. 9. Lag-time plots based on specific conductance for monitoring wells at site 1 and site 8.

'average' time that a specific conductance drop in the Great Miami River is recognized in a particular well. A lag time of 29 h was calculated for well 1I; this time corresponds closely to the median value (32 h) of visually chosen lag times for 18 events (gage height increases of greater than approximately 1 m) during the collection period. The calculated lag time for well 1A (138 h) also agrees with the median selected lag times (140 h) from the events. Lag times for temperature could not be visually selected from the 18 events.

The correlation coefficients for most of the monitoring wells indicate that specific conductance in the wells is highly correlated with specific conductance in the river; data from wells 1D and 8D, however, are not highly correlated. Calculated lag times from monitoring wells at site 8 are much longer (and less well correlated) than those at site 1. Because distances of flowpaths between the river and the monitoring wells are difficult to estimate and flow velocity, based on lag time is thus difficult to determine, the distance between monitor well screens was divided by lag times to determine the lag velocities among the wells. Lag velocities calculated from analyses of wells 1A, 1B, and 1C ranged from 2.1×10^{-3} to 6.0×10^{-3} cm/s; velocities for 8A, 8B, and 8C ranged from 3.5×10^{-4} to 7.1×10^{-4} cm/s. Lower velocities at site 8 may be due to the location of site 8 in the middle of the well field; traveltimes of water from the river and between wells are more affected by nearby well pumping than at site 1, causing circuitous travel pathways from the river to the production well.

The calculated specific conductance lag times are much less than the temperature lag times, as expected, because of the processes affecting temperature transport through the riverbed and aquifer. Because specific conductance is highly correlated with chloride concentrations in the river and aquifer, the calculated lag velocity also may be considered to represent the average advective groundwater flow velocity.

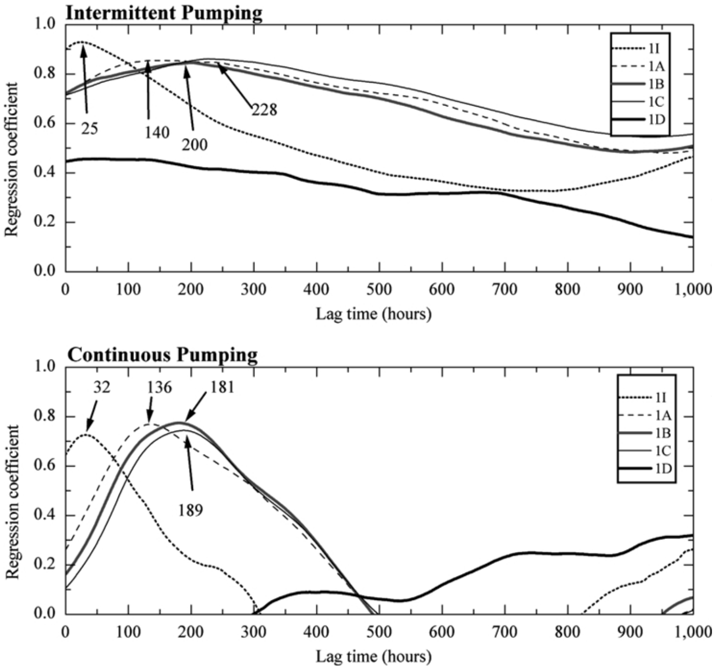

Fig. 10. Specific conductance lag-time plots for site 1 wells. From July 1999 to August 23, 2000, the production well at site 1 pumped intermittently; after August 23, 2000, the production well was pumped continuously.

6. Discussion

On August 23, 2000, pumping at production well 1 ceased to be intermittent (before that date, water demand and pump-servicing schedules determined when the pumps were run) and became continuous until April 2001. The cross-correlation results from these different pumping schedules are shown in Fig. 10.

Several issues that may affect well field management arise from examination of these plots. Except for the inclined well (1I), all lag times for continuous pumping were less than those during intermittent pumping. This finding indicates that, when the wells are pumped continuously, traveltimes from the Great Miami River to the production well are shorter than when the wells are cycled intermittently. This finding is consistent with the traveltime for a parcel of water from the river to the production well under a uniform and strongly downward gradient (continuous pumping) compared to the traveltime of a parcel of water if the gradient shifted intermittently from a strongly downward (pumping) gradient, to either a slightly downward gradient (recovery) or a slight upward gradient, toward the river. Moreover, the likelihood that a chemical or biological constituent from the river would arrive at the production well at a certain time would be more constrained under continuous pumping, as evidenced by the more distinct lag-time peaks. Therefore, if a production well under surface-water influence were pumped continuously, traveltimes would be somewhat faster than if the well were pumped intermittently. Because there is an average lag time of approximately 8.5 h between peak gage height and the specific conductance trough in the river, care should be taken when using peak gage height as the onset of contamination in the river.

The findings of this study illustrate that an easily measurable field parameter, specific conductance, measured at different depths and locations can be used to estimate advective traveltimes from a river to a production well. Traveltimes based on lag-time analyses of specific conductance were estimated for monitoring wells from 1.5 to 27 m into the Miami Valley Buried Aquifer, and they ranged from several hours to 3 months. Lag-time analysis of temperature resulted in much longer traveltimes, owing to the numerous processes that affect the transport of water temperature. An analysis of long-term continuous pumping of a production well compared to intermittent pumping indicates that a more effective sampling scheme to recognize surface-water effects can be designed under continuous pumping.

Acknowledgments

The authors thank the Ohio Water Development Authority; Miami University, Geology Department; and the Greater Cincinnati Water Works for supporting this project.

References

Bourg, A.C., Bertin, C., 1993. Biogeochemical processes during the infiltration of river water into an alluvial aquifer. Environ. Sci. Technol. 27, 661–666.

Brocklebank, J.C., Dickey, D.A., 1986. SAS System for Forecasting Time Series, SAS Institute Inc, Cary, NC.

Dove, G.D., 1961. A Hydrologic Study of the Valley-fill Deposits in the Venice Area, Ohio. Ohio Division of Water Technology, Report No. 4, Columbus, OH.

Gerba, C.P., Yates, M.V., Yates, S.R., 1991. Quantification of factors controlling viral and bacterial transport in the subsurface. In: Hurst, C.J., (Ed.), Modeling the Environmental Fate of Microorganisms, ASM Press, Washington, DC, pp. 77–87.

Gollnitz, W.D., Whitteberry, B., Vogt, J., Sheets, R.A., Rowe, G.L., Levy, J., Findlay, R.H., Mignery, M.B., 2000. Introduction to the flowpath study at the City of Cincinnati's C.M. Bolton well field—a case study for monitoring induced infiltration. 45th Annual Midwest Ground Water Conference, October 17–19, 2000, Columbus, OH, p. 9.

Grischek, T., Hiscock, K.M., Metschies, T., Dennis, P.F., Nestler, W., 1998. Factors affecting denitrification during infiltration of river water into a sand and gravel aquifer in Saxony, Germany. Water Res. 32 (2), 450–460.

Harvey, R.W., 1997. In situ and laboratory methods to study subsurface microbial transport. In: Hurst, C.J., Knudsen, G.R., McInerney, M.J., Stetzenbach, L.D., Walter, M.V. (Eds.), Manual of Environmental Microbiology, ASM Press, Washington, DC, pp. 586–599.

Hem, J.D., 1985. Study and interpretation of the chemical characteristics of natural water. US Geol. Surv. Water-Supply Pap. 2254.

Lee, D.R., 1977. A device for measuring seepage flux in lakes and estuaries. Limnol. Oceanogr. 22, 140–147.

Macler, B.A., 1995. Developing a national drinking water regulation for disinfection of ground water. Ground Water Monit. Rem. 15 (4), 77–84.

McDowell-Boyer, L.M., Hunt, J.R., Sitar, N., 1986. Particle transport through porous media. Water Resour. Res. 22, 1901–1921.

Metge, D.W., Harvey, R.W., Becker, M., Shapiro, A., Collins, S., Sheets, R.A., Rowe, G.L., 2000. What surrogates can tell us about the transport behavior of pathogens in fractured-rock and granular aquifers. EOS Transactions of the American Geophysical Union, 81(48), Fall Meeting (Suppl. Abstract B51C-03).

Sheets, R.A., Mignery, M.B., Whitteberry, B., 2000. Simulation of ground-water flowpaths in an area of induced infiltration. 45th Annual Midwest Ground Water Conference, October 17–19, 2000, Columbus, OH, p. 11.

Shindel, H.L., Mangus, J.P., Trimble, L.E., 2000. Water Resources Data, Ohio, Water Year 1999; vol. 1, Ohio River Basin, Excluding Project Data. Water Data Report, US Geological Survey, OH-99-1.

Smith, R.C., 1962. Cincinnati Water Works Ground-water Development, Miami River Area. Report prepared for Black and Veatch, Consulting Engineers, by Robert C. Smith & Associates, 25p.

Sun, K., Findlay, R.H., Levy, J., Brannock, J.M., Tomares, A.P., Mumy, K., Porter, J.A., 2000. Effect of sediment characteristics on bacterial transport through intact aquifer sediment cores. Summit 2000, Geological Society of American Abstracts with Programs, November 9–18, 2000, Reno, Nevada, 32(7), p. A-432.

US Environmental Protection Agency, 1998. Drinking water; national primary drinking water regulations, interim enhanced surface water treatment, final rule. Fed. Reg. 63 (241), 69477–69521.

Verstraeten, I.M., Carr, J.D., Steele, G.V., Thurman, E.M., Bastian, K.C., Dormedy, D.F., 1999. Surface water–ground water interaction: herbicide transport into municipal collector wells. J. Environ. Qual. 28 (5), 1396–1405.

Walling, D.E., Webb, B.W., 1980. The spatial dimension in the interpretation of stream solute behavior. J. Hydrol. 47, 129–149.

Walton, W.C., Hills, D.L., Grundeen, G.M., 1967. Recharge from induced streambed infiltration under varying groundwater-level and stream-stage conditions. Minn. Water Resour. Res. Cent., Bull. 6.

Wright, P.R., Cunningham, W.L., 1994. Use of rotosonic drilling for field investigations of ground water at Wright–Patterson Air Force Base, Ohio. Ground Water Mgmt. 18, 611–620.