Wisconsin Geological and Natural History Survey
3817 Mineral Point Road
Madison, Wisconsin 53705-5100
TEL 608/263.7389 FAX 608/262.8086
http://www.uwex.edu/wgnhs/

James M. Robertson, Director and State Geologist

Field Verification of Capture Zones for Municipal Wells at Sturgeon Bay, Wisconsin

Final Report to the Wisconsin Department of Natural Resources

Kenneth R. Bradbury
Todd W. Rayne
Maureen A. Muldoon

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FIELD VERIFICATION OF CAPTURE ZONES FOR MUNICIPAL WELLS AT STURGEON BAY, WISCONSIN

Final Report to the Wisconsin Department of Natural Resources

Kenneth R. Bradbury
Wisconsin Geological and Natural History Survey
University of Wisconsin-Extension

Todd W. Rayne
Department of Geology
Hamilton College

Maureen A. Muldoon
Department of Geology
University of Wisconsin-Oshkosh

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Abstract

Naturally-occurring seasonal and climatic variations in oxygen isotope ratios, temperature, and electrical conductivity act as natural tracers to help verify groundwater modeling in fractured dolomite near Sturgeon Bay, WI. A regional finite-difference model treats horizontal fracture zones as discrete flow zones and provides acceptable simulations of steady and transient hydraulic heads. This model was used to delineate the contributing areas for municipal wells in the city of Sturgeon Bay. However, the model was previously poorly constrained to flow velocities due to the technical and legal difficulties in performing controlled tracer experiments in this environment.

During 1999-2000 we repeatedly sampled groundwater at three deep wells along a 10-km groundwater flow path, and also collected sequential downhole geophysical logs (temperature, fluid conductivity) and continuous temperature and conductivity data from these wells.

Rapid and significant changes in water temperature and electrical conductivity occurred in response to recharge. In each well fluctuations in parameters were detected up to 150 ft below the water table within several hours of major recharge events. Borehole temperature/conductivity logs also show significant variation with time and depth, and clearly reflect the presence of hydraulically-active fracture zones. The near-complete vertical mixing in the upgradient well is consistent with our interpretation that significant recharge occurs there. The lack of shallow changes in temperature and electrical conductivity in the downgradient well suggests that significant recharge may not occur immediately adjacent to this well. Instead, the laterally-significant fracture zones at depth transmit water into this well and respond hydraulically to upgradient recharge.

Temporal variations in oxygen isotopes in recharge persist through the groundwater flow system. Values of $\delta^{18}O$ in precipitation in the study area fluctuated between -4 $^{o}/_{oo}$ and -16$^{o}/_{oo}$ SMOW. Groundwater $\delta^{18}O$ also fluctuated seasonally, with greatest fluctuations (2.6 $^{o}/_{oo}$) in the recharge areas and least fluctuation (1.1 $^{o}/_{oo}$) at the production well. Based on the isotopic data, minimum rates of vertical groundwater movement range from 13 to 115 ft/day following recharge events. Recharge is extremely episodic and variable, with most recharge occurring following snowmelt and large rainfall events in the early spring.

While the geochemical and isotopic data collected here cannot confirm the conceptual or numerical groundwater models near Sturgeon Bay they are consistent with the results of those models. Both the field study and the numerical model show that the dolomite aquifer responds very rapidly to precipitation events. In the model, the simulated travel time from recharge to city well 6 is eight days during a high-recharge simulation. In the field, the $\delta^{18}O$ signal was detected at well 6 nine days following a major recharge event. Upgradient recharge occurs through numerous vertical fractures that transmit water to regionally-important horizontal fracture zones. Groundwater moves laterally through these horizontal zones with velocities up to several mi/yr, and they are critical in controlling flow to production wells. Advective transport simulations using particle tracking produce concentration breakthrough curves consistent with field results.

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Background

During the past several years, hydrogeologists at the Wisconsin Geological and Natural History Survey and elsewhere have focused a great deal of effort to develop conceptual and numerical models of groundwater flow through fractured dolomite. The main motivation for the WGNHS's work in this area has been Wisconsin's wellhead protection program, which seeks to delineate capture zones for municipal wells in the state as part of Wisconsin's groundwater protection plan. Fractured dolomite forms a shallow aquifer in many parts of the state, and groundwater movement through such fractured rock is difficult to characterize and challenging to model. Over the last several years, the principal investigators have completed a major investigation delineating capture zones for five municipal wells serving the city of Sturgeon Bay, Wisconsin. This two-part study involved both a careful examination of the hydrostratigraphy of the Silurian dolomite in Door County (Muldoon and others, in press) and the construction of a three-dimensional groundwater flow model of the Sturgeon Bay area (Bradbury and others, 1998). Hydrostratigraphic characterization involved locating and characterizing vertical and horizontal fractures and high-permeability zones. Correlating stratigraphic interpretations with "hard" hydrogeologic and geophysical data such as gamma and flowmeter logs, packer tests, and fracture mapping produced a hydrostratigraphic model with 14 gently dipping high-permeability zones related to bedding planes or facies changes. Investigators used a three-dimensional numerical model (MODFLOW) combined with a particle tracking code (MODPATH) and a fracture-flow code (SDF) to simulate the groundwater system around Sturgeon Bay and to delineate capture zones for five municipal wells. The computer model was designed using the hydrostratigraphic model as a conceptual framework. Dipping fracture zones are simulated as thin high-permeability layers. The locations of exposed bedrock and surficial karst features were used to help quantify recharge.

Model results show that Sturgeon Bay's wells are extremely vulnerable to contamination. Capture zones for the municipal wells extend north and south from the city center and terminate outside the Sturgeon Bay city limits. Travel times for recharging precipitation to reach any of the city's well are generally less than one year even though the capture zones extend for several miles.

Controlled tracer experiments, in which substances are added to groundwater upgradient of a pumping well and later are detected at the well, are the ideal method for verifying both the geometry of the capture zones and for predicting groundwater travel times. In practice, however, such tracer experiments are very difficult and expensive to carry out for several reasons. First, Wisconsin generally prohibits the injection of chemicals into groundwater, and it is unlikely that legal permission would be granted for a controlled tracer experiment near a public supply well. Second, due to the tremendous dilution that occurs within the high-permeability fractures and as groundwater converges to a high-capacity well the initial tracer injection would need to be very large and concentrated. Third, sample acquisition and analysis would be logistically complex, tedious, and expensive.

An alternative method of verifying the model-predicted capture zones is to observe naturally-occurring variations in temperature, oxygen-18 and deuterium ratios, and electrical conductivity as they move through the groundwater system. These natural environmental tracers are easily detectable in groundwater, and their seasonal variation in recharge is easily characterized. While not as robust as controlled tracer experiments, this approach is relatively inexpensive and does not involve injection of chemicals into groundwater. If successful, this approach may provide a model for verification of capture zones in other parts of Wisconsin.

Acknowledgments

This project was funded in part by the Wisconsin Department of Natural Resources through the State of Wisconsin joint solicitation of proposals to conduct research and monitoring on groundwater. We thank Jake Beaulieu, UW-Oshkosh, for his assistance in collecting data at the field sites, Richard Weidman and the staff of the Peninsular Agricultural Research Station for collecting precipitation samples, and Todd Maurina and the staff of the Sturgeon Bay Utilities for collecting water samples from the production well.

Project objectives

This project evaluates the use of naturally-occurring seasonal and climatic variations in oxygen isotopes, temperature, and electrical conductivity as natural tracers to verify model-delineated zones of contribution for municipal wells at Sturgeon Bay, Wisconsin. The goals of the study were to improve our understanding of groundwater flow in this environment, to evaluate the use of natural groundwater tracers in wellhead protection studies, and to verify existing conceptual and numerical models of groundwater movement near Sturgeon Bay. Natural precipitation varies seasonally in oxygen isotope ratio and temperature, and the electrical conductivity of recharge water also varies throughout the year. These variations compose a signal that should remain imprinted on groundwater in the Sturgeon Bay area during its relatively rapid movement from recharge to pumping wells. Sampling precipitation and groundwater at several points throughout a mapped capture zone should allow this signal to be traced through the groundwater flow path. Comparison of groundwater samples to precipitation samples can provide a relatively inexpensive way to confirm the model-predicted groundwater flow velocities.

Methods

Selection of field sites

The field sites selected for sampling are generally, but not exactly, along a groundwater flow path from a recharge area toward municipal wells in Sturgeon Bay. This project did not include money for installing new wells, and so we have chosen existing wells for monitoring. Figure 1 shows an overview of the study area. Groundwater flows generally from northeast to southwest, beginning at a potentiometric high near the center of the county and discharging into Sturgeon Bay (Bradbury and others, 1998). Municipal wells (wells 3, 6, 7, 8, and 10) intercept some of this groundwater for local supply. The shaded area on figure 1 represents the model-delineated zone of contribution for Sturgeon Bay municipal wells 6 and 7. The model showed that the zones of contribution for these two wells merge and overlap (Bradbury and others, 1998). In order to quantify changes in groundwater parameters along this zone of contribution we chose to monitor three existing wells. In upgradient to downgradient order these are Dr-339, Dr-265, and city well 6 (Dr-13).

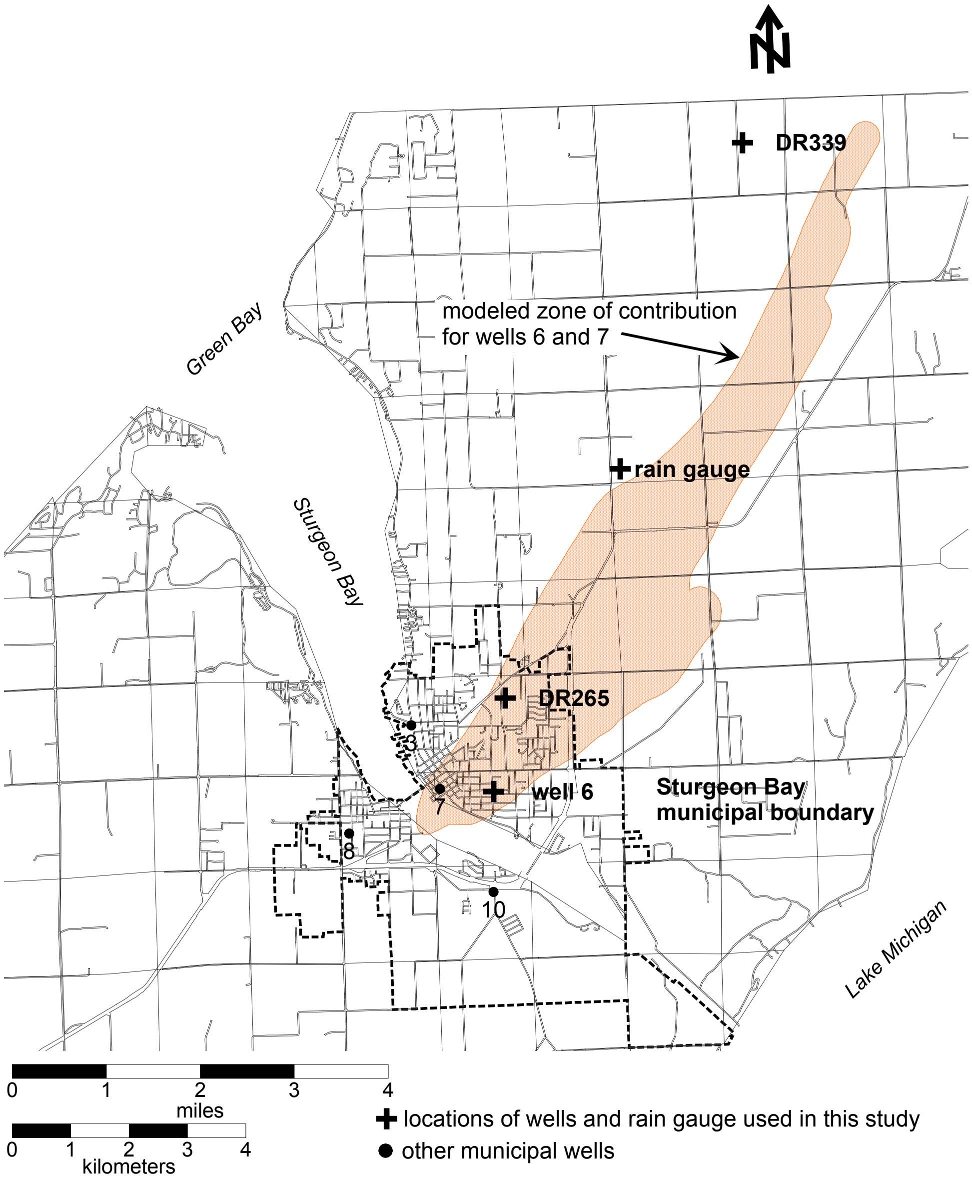

Figure 1. Study area, showing the location of the simulated contributing area for city well 6 and the locations of monitoring points used in this study.

Upgradient site-Dr-339

Well Dr-339 is an observation well located in a recharge area near the center of the Door Peninsula. This well was chosen as representative of conditions in the recharge area even though it is not directly in the zone of contribution for city well 6. Well Dr-339 is 240 ft deep, cased to 40 ft, and the depth to water in the well fluctuates between about 150 and 200 ft (fig 2). The well is in a rural woodlot surrounded by agricultural fields. Bedrock is shallow (depth of 1-3 ft), and numerous small karst and solution features occur in the area (Bradbury and Muldoon, 1992). Muldoon and others (in press) delineated important horizontal high-hydraulic conductivity fracture zones intersecting this well at depths of about 140, 210, and 240 ft (fig 2).

Intermediate site-Dr-265

Well Dr-265 is an observation well located at the Door County Highway Department facilities on the north side of the City of Sturgeon Bay. This well is in urban surroundings and is near highways and salt storage facilities. Dr-265 is 440 ft deep, is cased to 170 ft, and the water level in the well fluctuates between 0 to 40 ft below the surface (the well sometimes flows under artesian head). Bedrock occurs at about 10 feet below the land surface. Muldoon and others (in press) delineated important horizontal high-hydraulic conductivity fracture zones intersecting this well at depths of about 170, 210, 260, 280, 290, and 380 ft (fig 2).

Downgradient site- city well 6

City well 6 (having WGNHS number Dr-13) is an operating municipal well located in central Sturgeon Bay on the north side of the Sturgeon Bay canal. This well is 425 feet deep, cased to 212 feet, and the static depth to water in the well is about 20 feet. Well 6 produces about 710 gallons per minute (McMahon Associates, 1991), which is piped into the municipal system. Routine sampling by city managers showed that this well was contaminated with bacteria, and the Water Utility operates an ozone treatment system on this well to treat the bacterial contamination.

Precipitation

Daily precipitation and air temperature data were measured and recorded by personnel at the Peninsular Agricultural Research Station, University of Wisconsin-Extension, located about 3 miles north of the city (fig 1). Precipitation samples were collected from a standard rain gauge at the research station.

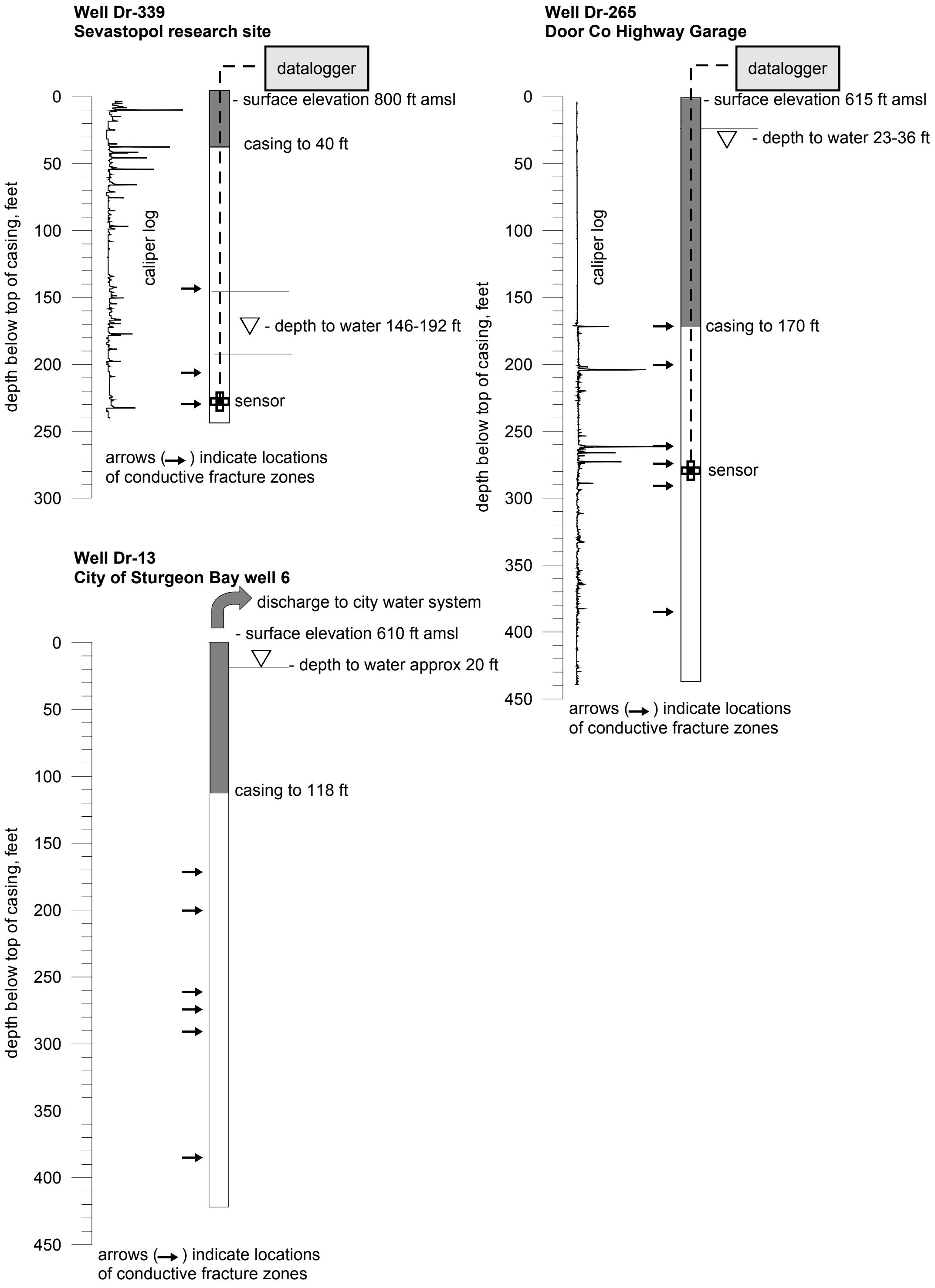

Figure 2. Construction details of the three wells monitored in this study.

Instrumentation and sample collection

Electrical conductivity and temperature

Electrical conductivity and temperature of groundwater were monitored continually at Dr-339 and Dr-265. Each of these wells was instrumented with a downhole temperature/conductivity probe (Campbell Scientific (CSI) model 247WL) connected to a digital datalogger (CSI model CR10X). The probes were suspended from cables lowered into the well bores to positions adjacent to major horizontal fractures (fig 2). Temperature and conductivity at each site were measured once per minute and averaged over 15 minutes; the 15-min averages were stored in the datalogger and downloaded each month to a portable computer. The specified accuracy of these probes is +/- 0.4 ^{o}C for temperature and +/- 5% for electrical conductivity (CSI, 1996).

Water levels

We measured the depth to water in wells Dr-339 and Dr-265 manually using an electrical water-level indicator tape. Measurements were taken approximately monthly during site visits.

Borehole logging

In wells Dr-339 and Dr-265 we obtained downhole profiles of fluid electrical conductivity and temperature at approximately monthly intervals using a Mt Sopris 1000 digital borehole logger and combination temperature/conductivity probe. In order to minimize disturbance to the water column in the well, logs were run prior to sampling and the logging speed was approximately 10 ft/min. All log data were recorded relative to the depth from the top of the casing.

Collection and analysis of water samples

We obtained periodic water samples at all sites. At approximately monthly intervals, we collected water samples from wells Dr-339 and Dr-265 using a submersible Grundfos sampling pump. The pump was lowered into the well to a point opposite the major fracture zone penetrated by each well. The well was pumped slowly until the electrical conductivity and temperature of the discharge water stabilized, and samples were collected in polyethlyene bottles. Personnel of the Sturgeon Bay Utilities collected daily or weekly samples from city well 6 at the well sampling tap. Because this well was in active use it was not possible to install continuous recorders or perform geophysical logging. WGNHS personnel measured electrical conductivity on the samples collected from city well 6 using a Hach field conductivity meter. Precipitation samples at the Peninsular Research Station were collected from a standard rain gauge following precipitation events and placed in polyethylene sample bottles. Sample analyses for isotopes (^{18}O and ^{2}H) were performed by the Environmental Isotope Laboratory at the University of Waterloo (Ontario).

Results

Precipitation and water level fluctuations

The frequency and intensity of precipitation events control groundwater recharge in central Door County. Figure 3 summarizes precipitation and water-level fluctuations during the data collection period, which ran from August, 1999, through August, 2000. During this period, precipitation was abnormally low, totaling 23.55 inches of water from both rain and snow. The 30-year average annual precipitation measured at the Peninsular Research Station is 31.49 in. Precipitation during the fall and winter of 1999 had little effect on groundwater levels, as water levels in wells Dr-265 and Dr-339 declined steadily throughout this period. The major recharge event during the study period occurred in late February, 2000, when several days of rain coincided with warm temperatures to melt the winter snowpack. The combined rainfall and snowmelt generated the major recharge event for the study period. During the last few days of February, the water level in Dr-339 rose by nearly 50 feet and the water level in Dr-265 rose by about 20 feet. Such rapid, high-magnitude water level fluctuations are characteristic of recharge periods in Door County, and in fact are not as extreme as fluctuations recorded in years having more typical precipitation (Bradbury and Muldoon, 1992). Following the late February event other less significant recharge events occurred following major storms in April, May, and June.

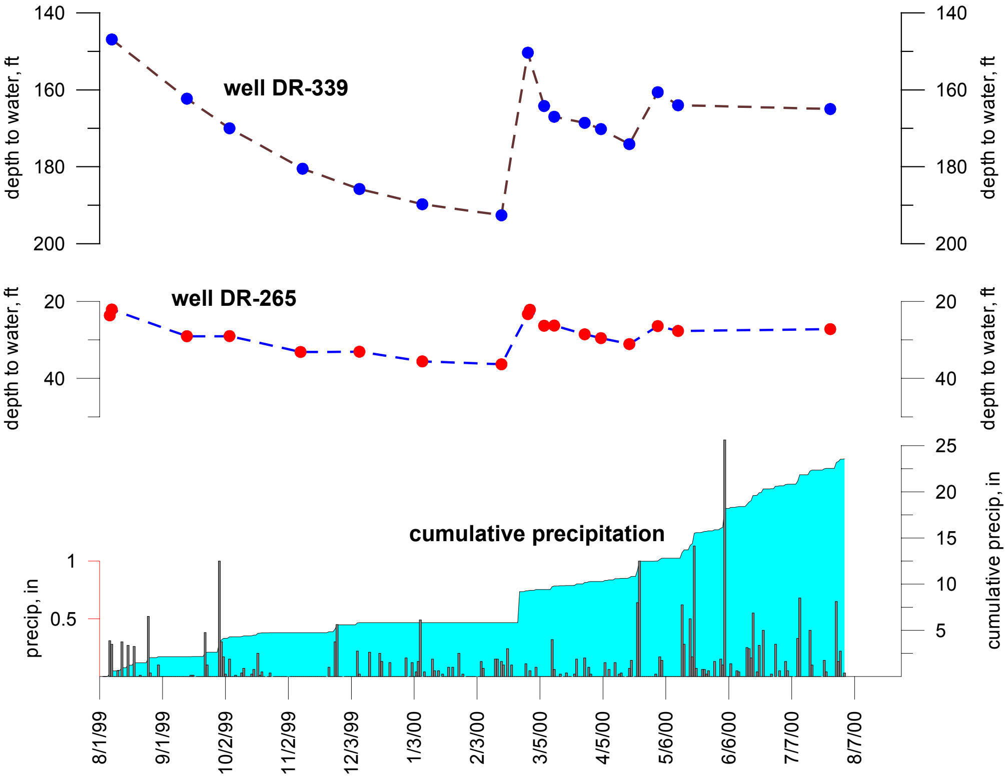

Figure 3. Water levels and precipitation during the study period.

Summary of geochemical data

Table 1 summarizes the geochemical data collected as part of this study. Groundwater at the upgradient well (Dr-339) has lower electrical conductivity, lower temperature, and is isotopically lighter than water at the downgradient well (Dr-265). Water from the production well (well 6) has parameter values about midway between values from the other two wells. These results are consistent with our overall conceptual model of the flow system. Recharge to well Dr-339 occurs in a wooded area with few nearby solute sources. As the groundwater moves downgradient toward Dr-265 the water dissolves dolomite, and the total dissolved solids increase. Near Dr-265 there are numerous sources of dissolved ions, notably the salt storage warehouse near the well and the highways and urban land use on the north side of the city of Sturgeon Bay. In our conceptual and numerical models of the flow system, groundwater follows nearly vertical recharge paths in the central portion of the county and then flows within distinct near-horizontal high-permeability zones as it moves laterally to the discharge area. These near-horizontal flow horizons are easily identified in the borehole geophysical data below. City well 6 produces a mixture of water from various flow horizons within the aquifer and its intermediate chemistry is expected.

Continuous temperature/electrical conductivity monitoring

Rapid and significant changes in water temperature and electrical conductivity occurred in the two wells (Dr-339 and Dr-265) equipped with continuous recorders. These changes show the discrete nature of recharge events in the study area, and also show how rapidly recharge moves into the groundwater flow system. Figure 4 (top portion) shows the continuous record for Dr-339 from August, 1999 through July, 2000. Water temperature in this well was nearly constant at about 8.1 ^{o}C and electrical conductivity was also nearly constant at about 0.5 mS/cm. There are two notable anomalies in this record, both associated with recharge events. The first, occurring on 2/26/99, corresponds to a period of snowmelt following several days of light, warm rain. All of the winter snowpack in the study area disappeared during this period. Simultaneously, the groundwater temperature rose rapidly by about 0.1 ^{o}C, and electrical conductivity fell slightly. The water level in this well, which had been declining steadily since measurements began in August, rose rapidly nearly 45 ft. Following the February event, the water level in Dr-339 declined gradually, the water temperature declined to background over about a 10-day period, and electrical conductivity returned to background values.

The second major recharge event at Dr-339 occurred on April 26, 2000, following two days of intense rainfall. Water temperature declined rapidly and significantly from about 8.1 to less than 7.9 ^{o}C, and electrical conductivity also declined slightly. The groundwater level rose about 15 ft during this period. After this event there was littler temporal variation in the measured parameters through the end of the study, even though there were several large precipitation events during the late spring and early summer

Table 1. Summary of geochemical and isotopic data

Site	*statistic*	*electrical conductivity, mS*	*Temperature, ^{o}C*	$\delta^{18}O$, $^{o}/_{oo}$	$\delta^{2}H$, $^{o}/_{oo}$
Precipitation	mean	0.07	7.87*	-9.14	-62.77
	std dev	0.04	9.75*	3.45	32.61
	min	0.02	-16.11*	-16.37	-120.50
	max	0.14	25.00*	-4.32	-29.48
	N	9	366*	10	7
	CV	0.85	1.23*	-0.37	-0.52
Dr-339	mean	0.55	8.09	-11.00	-80.51
	std dev	0.04	0.03	0.67	6.00
	min	0.40	7.86	-12.87	-89.43
	max	0.63	8.44	-10.25	-76.43
	N	7667	7667	12	4
	CV	.073	0.0037	-0.061	-0.075
Dr-265	mean	2.32	9.10	-10.13	-72.60
	std dev	1.35	0.08	0.60	7.81
	min	0.90	8.93	-11.82	-82.04
	max	18.32	9.35	-9.46	-65.73
	N	7545	7545	11	4
	CV	0.581	0.0088	-0.059	-0.107
well 6	mean	0.89	**	-10.28	-71.30
	std dev	0.06	**	0.25	1.75
	min	0.68	**	-10.93	-74.46
	max	1.15	**	-9.86	-68.15
	N	188	**	43	14
	CV	0.067	**	-0.02	-0.025

* averages of daily min and max air temperatures

**temperature data not collected at well 6

Temporal changes at well Dr-265 were more pronounced than at well Dr-339. Figure 4 (bottom portion) shows the record from Dr-265. It is important to note that the temperature/conductivity probe in this well was installed approximately 150 ft below the water table and so the variations in parameters discussed below rapidly penetrated deep into the saturated zone. Water temperatures and conductivity in this well are very responsive to precipitation events. Beginning in September, 1999, the temperature in Dr-265 increased rapidly by about 0.1-0.2 ^{o}C following almost all significant precipitation events (events greater than 0.5 in). Water temperatures declined to background values during the time between events. Simultaneously, electrical conductivity decreased measurably (by about 1 mS/cm) during most significant precipitation events, but also *increased* during some of the larger events. The most significant increase in electrical conductivity occurred during the snowmelt event of 2/26/00, when values increased from a background of about 2 mS/cm to nearly 15 mS/cm. Water temperature also increased during this event, and the water level in the well rose by about 15 ft. Following the snowmelt event the electrical conductivity returned to background values within 10 days.

Well Dr-265 also responded to the recharge event on 4/26/00. Immediately after this event the temperature in Dr-265 dropped by about 0.1 ^{o}C, and electrical conductivity also decreased slightly, while the water level in the well rose by about 5 feet. Following this event, the temperature continued to decline gradually until early June, and then rose, apparently in response to spring rains. Electrical conductivity was relatively steady through May and June.

The electrical conductivity in city well 6 (figure 5) generally ranged between 0.85 and 0.96 mS/cm, with several short-duration spikes in the data. Rapid, short-term rises in electrical conductivity occurred about 8/18/99 and 9/21/99, both following periods of rainfall. A minimum electrical conductivity of 0.68 mS/cm occurred about 12/3/99 following a period of no precipitation. The well showed near-steady electrical conductivity through the winter, with a slight increase following the recharge event on 2/26/00 and several short-duration increases from late April through mid-May, 2000. Two additional spikes occurred during late June and early July, 2000.

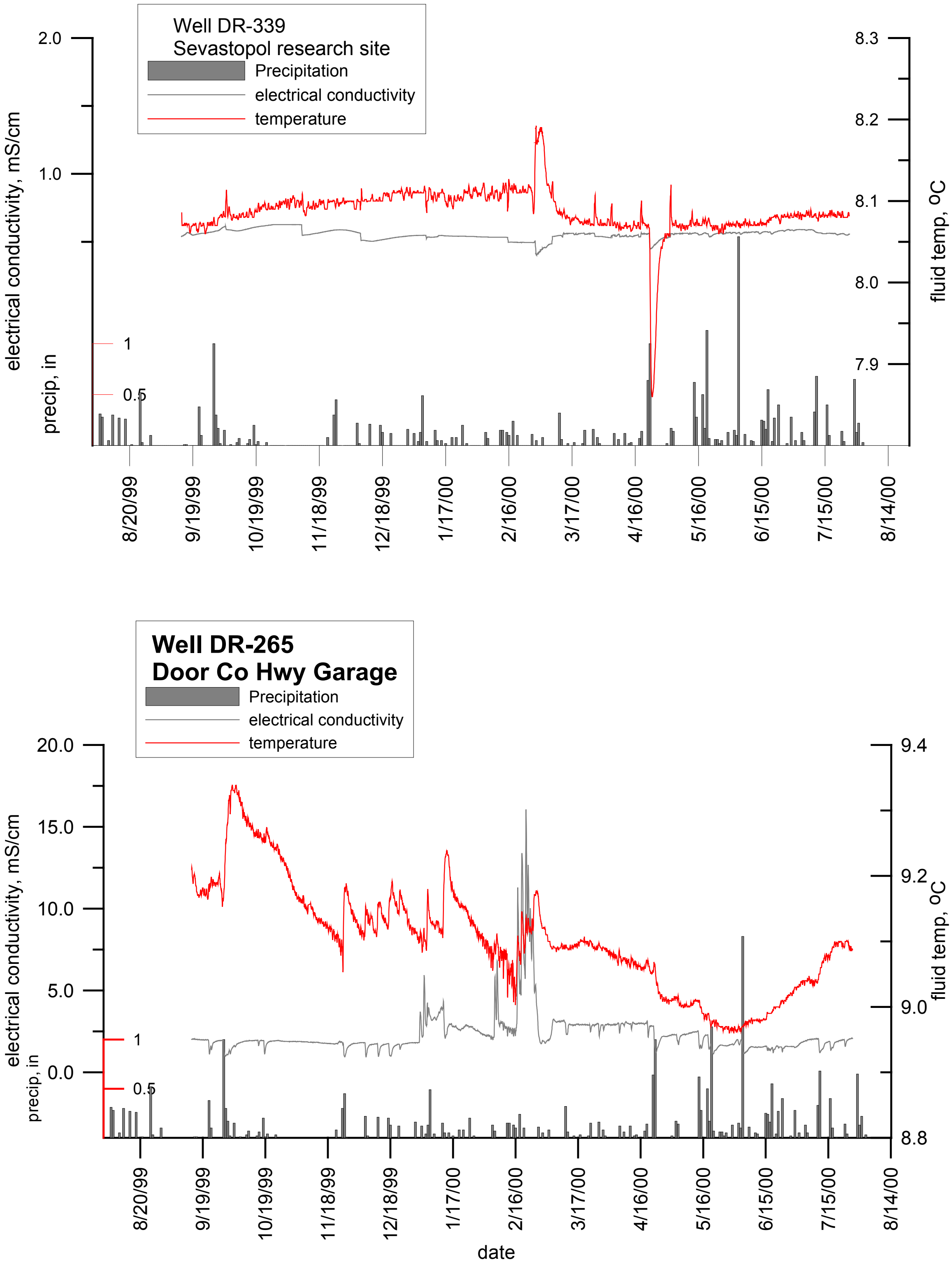

Figure 4. Temperature and electrical conductivity results at wells DR-339 and DR-265, shown with the precipitation record.

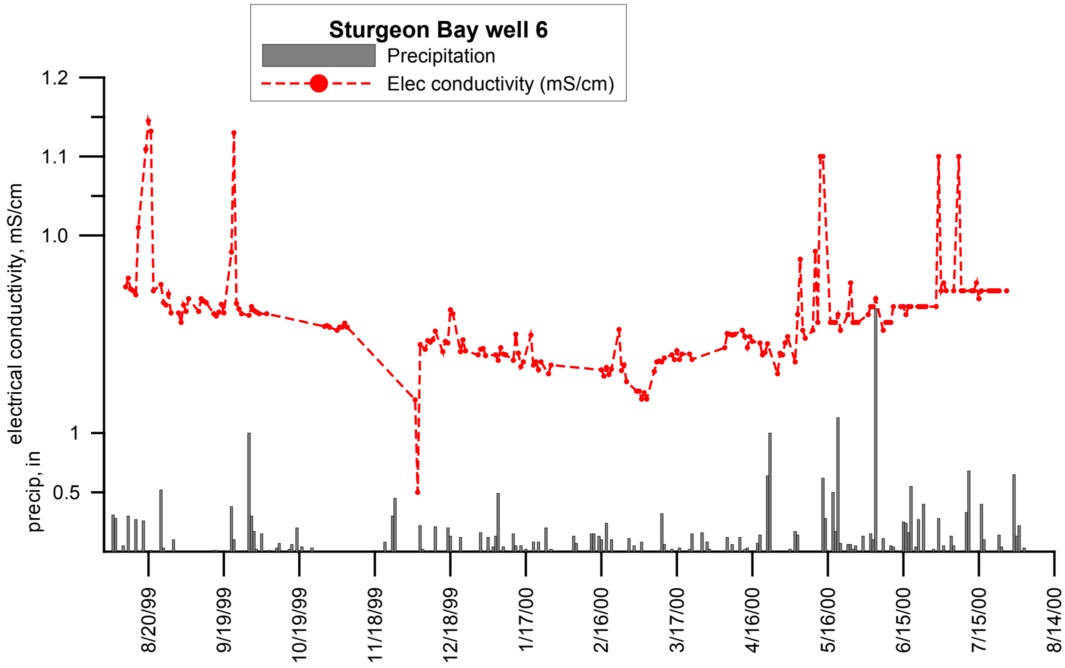

Figure 5. Temperature and electrical conductivity results at city well 6 (Dr-13), shown with the precipitation record.

Fluid Temperature and Fluid Conductivity Logs

Fluid temperature and resistivity/conductivity data can be acquired easily and rapidly in any open borehole. Sharp changes in these profiles, within a given borehole, provide a qualitative method of locating discrete high-permeability features where water of differing chemistry or temperature is flowing into or out of the borehole.

We conducted fluid temperature and conductivity/resistivity logs at wells Dr-265 and Dr-339 approximately monthly over the duration of the project; logging frequency was increased to approximately weekly during the spring of the year. One of the goals of the logging was to determine whether there were any temporal changes in which fractures were dominant in supplying water to the wells. We could than adjust our sampling depth to capture water coming in at the most significant fractures. In addition, we hoped that any changes seen in the sequential temperature and conductivity logs throughout the year would help us track recharge pulses.

Dr-339 Results

The water column in upgradient well Dr-339 was quite uniform with respect to temperature and fluid conductivity, indicating rapid and complete mixing of groundwater during most of the year. Unusually low groundwater levels during the study period apparently contributed to these fairly uniform results. Previous investigations of this well detected large, water-bearing fractures at depths of 150, 180, and 231 feet (Bradbury and Muldoon, 1992), and in previous years these fractures caused marked inflections in borehole temperature and fluid conductivity logs. However, the logs collected during the present study showed little response at these depths, probably because of the anomalously low precipitation and recharge that occurred during the monitoring period. Representative temperature fluid resistivity logs from Dr-339 collected during this study are plotted in figure 6. The sharp inflection seen at the top of many of these logs is due to the probe entering the water; the sharp deflection at the bottom is believed to be due to the probe entering soft sediment that has accumulated at the base of the well.

The logs show little temperature variation with depth; two logs – 11/6/99 and 3/4/00 -- have inflections that appear indicative of fracture inputs. The November log has a minor inflection at 195 ft (which correlates well with the fluid resistivity log) while the March log has a very pronounced inflect at approximately 178 ft. This very pronounced temperature change in March suggests that recharging snowmelt penetrates quickly to this depth and then perhaps moves laterally through the system since the water below 178 ft shows little temperature variation for the rest of the year.

The fluid conductivity logs were somewhat more variable than the temperature logs. Logs from 8/9/99 (approx 155 ft), 11/6/99 (approx 192 & 227 ft), and 3/4/00 (approx 167, 171, & 178 ft) all show one or more inflections in the profile (fig 6). What is interesting is that no two logs show inflections at the same depth. This suggests that as the water level fluctuates, different fractures dominate the flow near the well.

Dr-265 Results

Borehole logs collected at Dr-265 (figures 7 and 8) show significant variation with time and with depth, and clearly reflect the presence of hydraulically-active fracture zones at depth. Throughout the monitoring period there are inflections in both the temperature and fluid conductivity logs at depths of 265 ft and 380 ft; these inflections are particularly sharp following the recharge events of late February and mid-April, 2000.

When viewed sequentially, both the temperature (fig 7) and fluid conductivity (fig 8) logs show that fracture zones at 265 and 380 feet control groundwater flow into and out of Dr-265, and that flow occurs laterally rather than vertically. Recharge events control the dynamic nature of this well. Referring back to figure 2, recharge during the study period occurred in two distinct events. The first event was the rain and snowmelt during late February, and the second was a major rainstorm in late April. Both events altered the thermal and chemical profiles in well Dr-265. In figures 7 and 8 the profiles are numbered sequentially, and the profiles related to the February and April events are separated at the bottom of the figures. The dynamics of recharge and fracture inflow control the sequential profiles, as follows (the numbers below refer to profiles on the figures).

1. (1/5/00) Following a period of frozen ground and no recharge, the profiles are nearly vertical with a major inflection to the left (cooler, lower total dissolved solids [TDS] water) corresponding to a fracture zone at 265 feet. This appears to be the stable profile for the well. Previous straddle packer experiments (Bradbury and others, 1998) showed that under non-recharge conditions this fracture zone has lower hydraulic head than any other point in the borehole. Accordingly, it appears that, under non-recharge conditions, water leaves the borehole at this point. A second inflection back to the right (warmer water, higher TDS) corresponds to a fracture zone at 380 feet. One reasonable explanation for this profile is that under non-recharge conditions the lower fracture has a higher head than the upper fracture. Water flows into the borehole from the lower fracture and exits through the upper fracture.

2. (2/13/00) Little or no recharge has occurred and the profiles are nearly identical to the January profiles.

3. (2/27/00) Immediately following a major cold-weather recharge event the profiles are nearly vertical, and the 265 ft inflection disappears. However, the profiles revert to the earlier shape below the 380-ft fracture. The lack of change in the profiles above the upper fracture zone suggests that little vertical recharge occurs in the vicinity of this well. Instead, recharge at upgradient positions in the watershed causes higher heads in the 265 ft fracture. Flow in this fracture then reverses, and water flows downward through the borehole to exit in the lower fracture at 380 ft.

4. (3/10/00) The profiles are similar to profile 3, but show a slight shift to the left as the heads in the two fracture zones begin to equilibrate.

5. (4/2/00) The profiles are intermediate between the recharge profiles (3) and the steady profiles (1 and 2). The system is still equilibrating from the February event.

6. (4/16/00) The profiles are nearly identical to the steady profiles (1 and 2) suggesting that the transient February recharge pulse has passed.

7. (4/30/00) The profile is similar to profile 3, and corresponds to recharge following heavy

rains in late April. It is interesting to note that the temperature profile is nearly identical to the late February profile even though the April recharge water should have been significantly warmer than the February snowmelt. This suggests again that recharge occurs upgradient of this well and the well actually "sees" older water that has resided in the aquifer for several days or weeks. This water flows into the well in response to recharge at upgradient positions in the flow system.

8. (5/1/00) These profiles are similar to profile 5, and represent an intermediate stage as the effects of the April recharge event dissipate.

Taken together, the borehole logs obtained from wells Dr-339 and Dr-265 characterize a dynamic, transient groundwater flow system, with recharge occurring in relatively short but significant transient pulses. The near-complete mixing in upgradient well Dr-339 is consistent with our interpretation that significant recharge occurs near there. The lack of shallow changes in temperature and electrical conductivity in downgradient well Dr-265 suggests that significant recharge may not occur immediately adjacent to this well. Instead, the laterally-significant fracture zones at depth transmit upgradient recharge water laterally into this well.

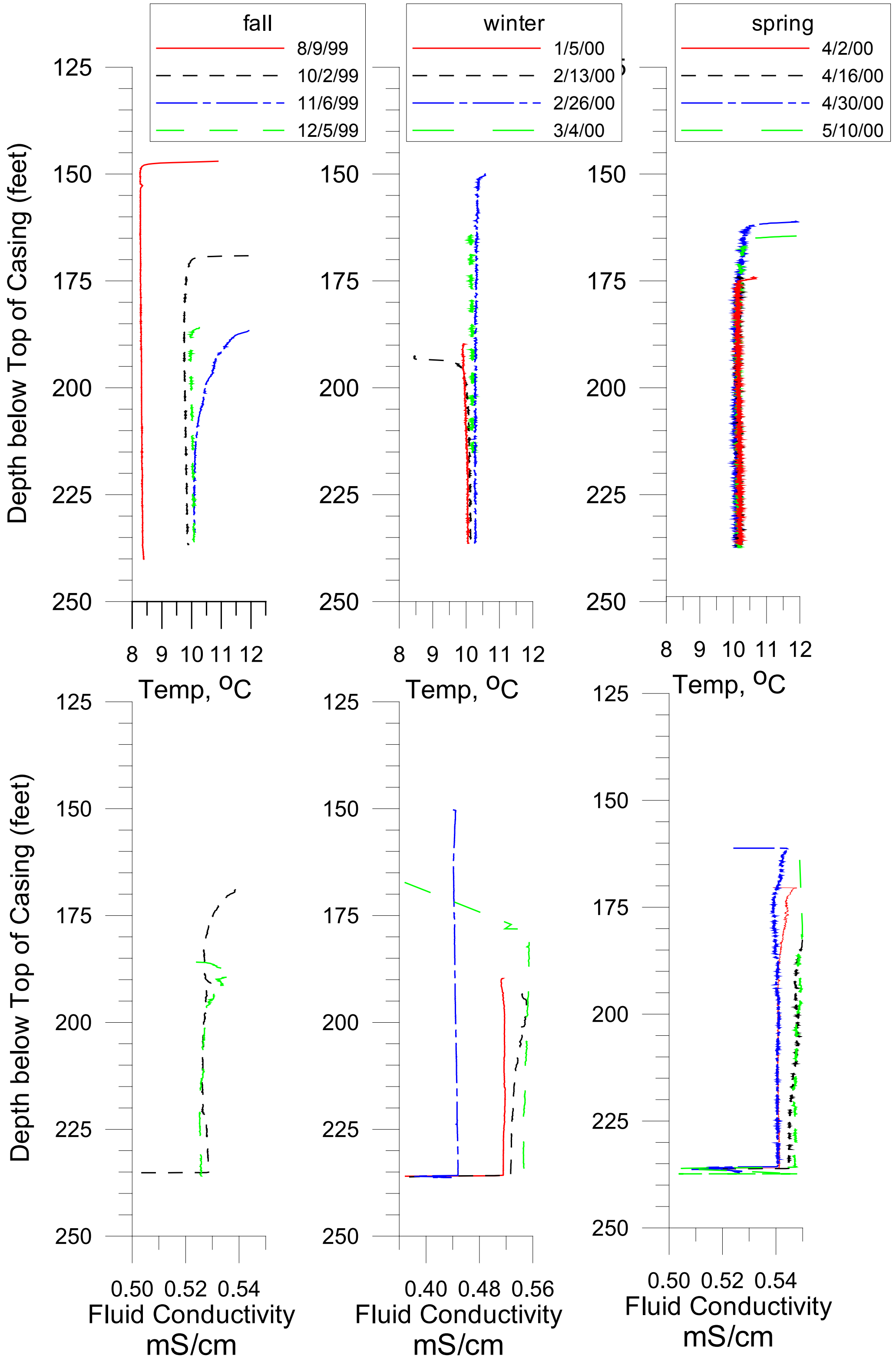

Figure 6. Temperature and fluid conductivity logs from well DR-339; upgradient well.

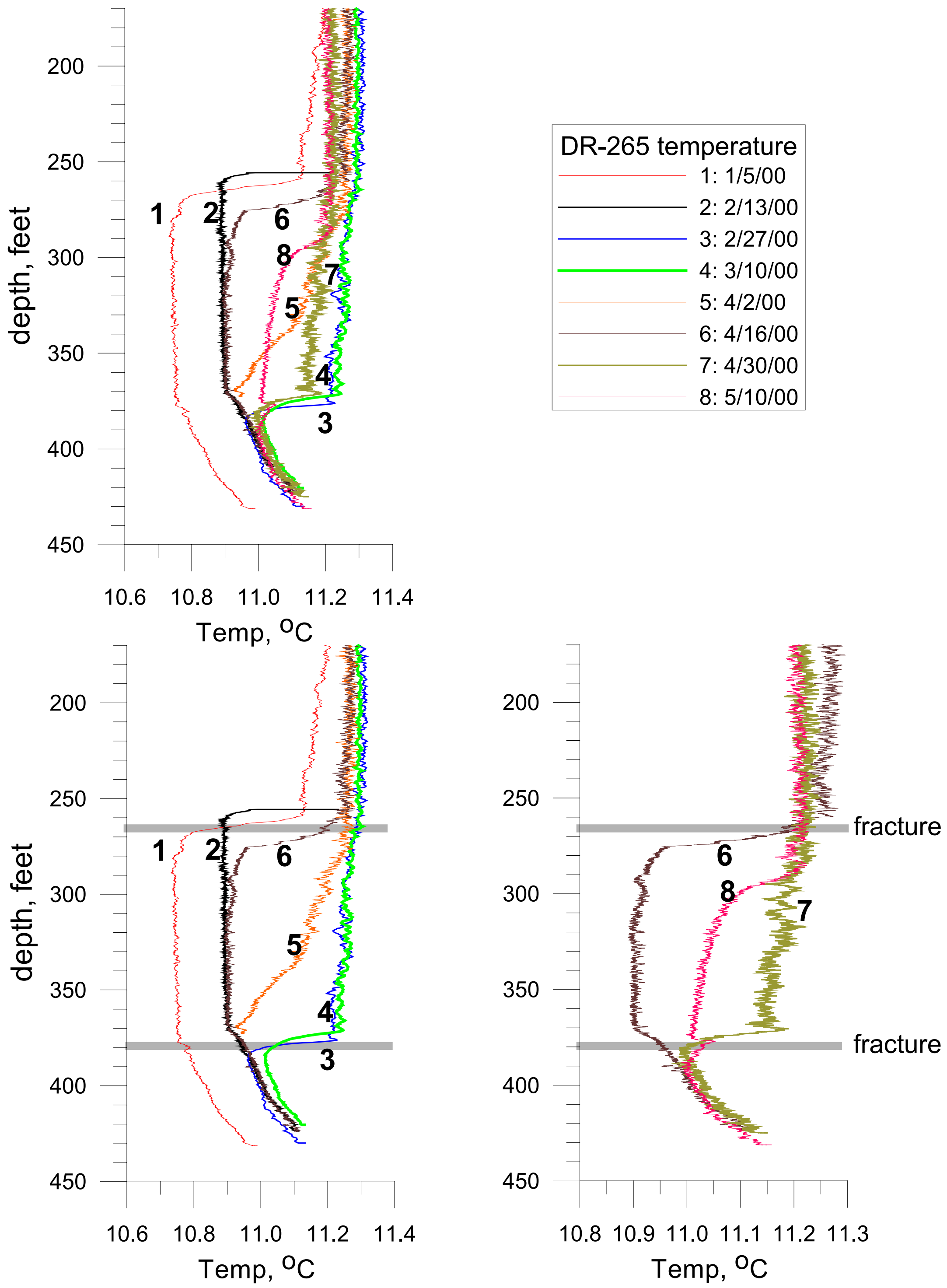

Figure 7. Selected downhole temperature logs from well Dr-265. Top figure shows all profiles; bottom figures show sequential profiles around the February (left) and April (right) recharge events.

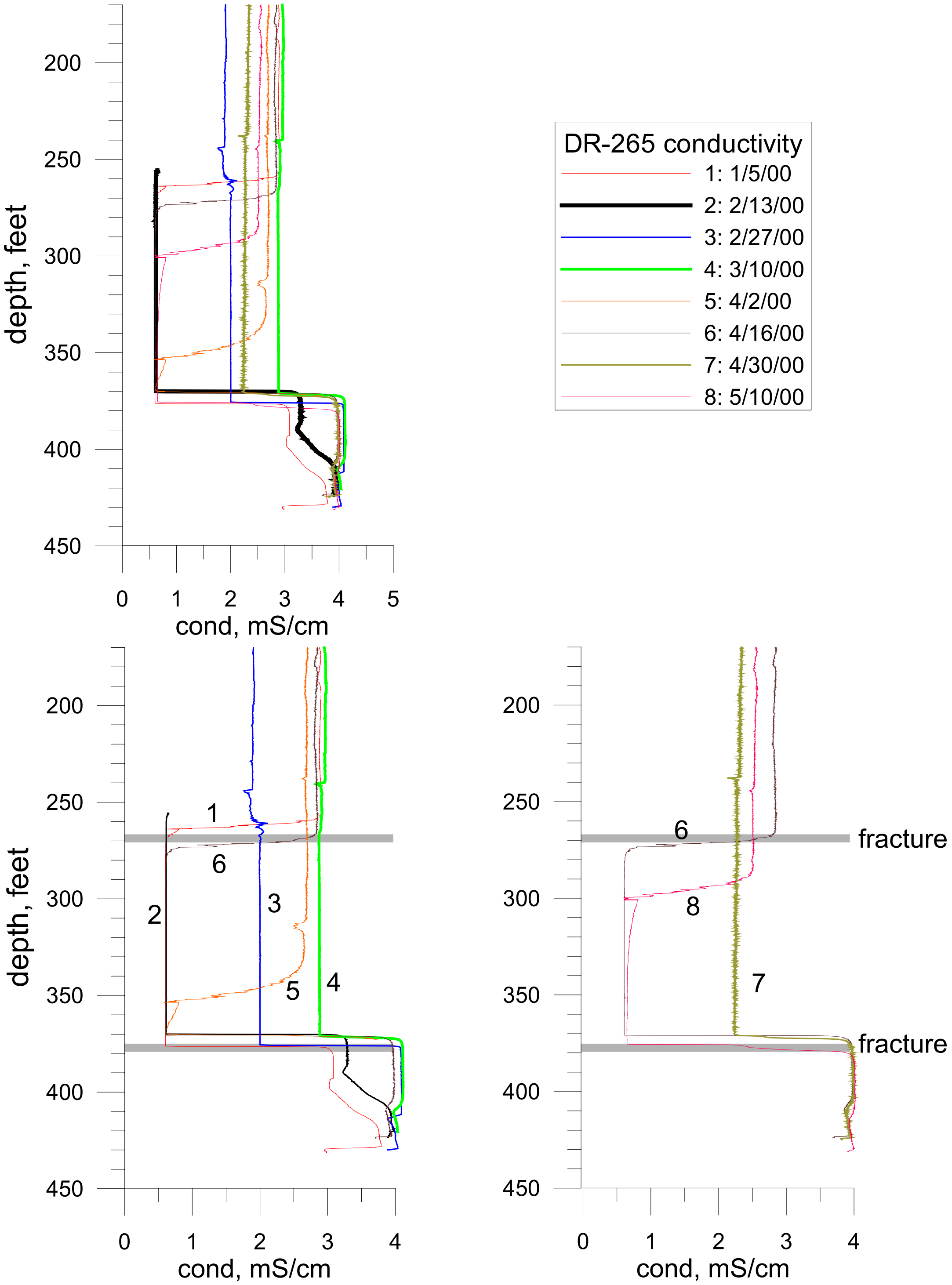

Figure 8. Selected downhole fluid electrical conductivity logs from well Dr-265. Top figure shows all profiles; bottom figures show sequential profiles around the February (left) and April (right) recharge events.

Isotopic Results

Oxygen-18 (^{18}O) and deuterium (^{2}H) are naturally-occurring stable isotopes commonly used in hydrologic studies. In water, these isotopes are incorporated into the water molecule and so are excellent groundwater tracers. Both isotopes become fractionated during repeated evaporation and precipitation cycles in the atmosphere, but undergo little or no additional change in shallow groundwater systems. Accordingly, in groundwater these isotopes usually reflect the isotopic composition of the recharge water, and temporal and spatial variations in isotopic content of groundwater result either from changes in recharge composition or from mixing in the subsurface. Seasonal temperature fluctuations are the main control on ^{18}O and ^{2}H composition in precipitation in the study area. These atmospheric changes are transmitted through the groundwater system. Concentrations of these isotopes are expressed in del (δ) notation as deviations in permil ($^{o}/_{oo}$) from concentrations in Standard Mean Ocean Water (SMOW).

Stable isotopic ratios of both ^{18}O and ^{2}H varied significantly with time and location during the sampling period. The relationship between these two isotopes is linear and does not differ significantly from the worldwide meteoric water line (fig 9). The linear relationship shows that post-meteoric fractionation of these isotopes is not significant in the study area. Such fractionation commonly occurs in lakes and wetlands, as the oxygen isotope ratios become proportionally more negative due to surface water evaporation. The lack of significant deviation from the meteoric water line in figure 9 shows that the sampled wells do not contain significant groundwater originating as surface water and that ^{18}O should be a conservative groundwater tracer in the study area.

Temporal variations in oxygen isotopes in recharge persist through time in the groundwater flow system (fig 10). Values of δ^{18}O in precipitation in the study area fluctuated between -4 $^{o}/_{oo}$ and -16$^{o}/_{oo}$ and are strongly correlated with mean air temperature. Groundwater δ^{18}O also fluctuated seasonally, with greatest fluctuations (2.6 $^{o}/_{oo,}$ coefficient of variation 0.061) in the recharge areas near Dr-339, less fluctuation in Dr-265 (2.4 $^{o}/_{oo}$, cv 0.059) and least fluctuation (1.1 $^{o}/_{oo,}$ cv 0.020) at downgradient city well 6 (table 1).

The late February 2000 snowmelt and recharge event was associated with a significant shift to more negative δ^{18}O values in all three wells (fig 10). During the period between 2/23/00 and 3/1/00 (indicated by vertical lines on the figure) the air temperature remained above freezing and several low-intensity rain events occurred in the study area. This combination of light rain and warm temperatures completely melted the snowpack. Although the snowmelt was not sampled, it presumably contained water with δ^{18}O values in the –16 to –12 $^{o}/_{oo}$ range, based on the precipitation sample collected in January. During or immediately following this event, samples collected from wells Dr-339 and Dr-265 contained, respectively, -12.87 $^{o}/_{oo}$ and –11.82 $^{o}/_{oo}$ δ^{18}O, and within several days (on 3/3/00) the δ^{18}O in city well 6 dropped to –10.93 $^{o}/_{oo}$, its minimum value for the entire sampling period.

Discussion

Isotopic shifts recorded in all three wells monitored during the project took place in response to the late February recharge event. We stress that the samples from wells Dr-339 and Dr-265 were obtained in the aquifer far below the water table, and so these data show that recharge water penetrates deeply into the aquifer in a matter of days. Prior to 2/23/00 the average air temperature in the study area was below freezing, there had been no precipitation for several days, and there was a thin snowpack over the landscape. The water sample from Dr-339 having $\delta^{18}O$ of -12.87 $^{o}/_{oo}$ was collected on 2/25/00, or 2 days later, and was obtained by pumping adjacent to a major fracture near the bottom of the well, 230 ft below the surface. Based on these distances, the minimum average vertical velocity of water moving from the surface to the sampling point was 115 ft/day and represents flow through the saturated zone and overlying unsaturated zone.

The vertical velocity calculation at well Dr-265 is more complex because the downhole geophysical logs (discussed above) suggest that recharge must take place at some distance upgradient of the well. Water moves into the well along horizontal fracture zones, but this travel distance is unknown. Accordingly, velocity estimates at Dr-265 underestimate the true travel distance and so underestimate the vertical velocity of the recharge pulse. At well Dr-265 the depth from the land surface to the sampling point is 280 feet. The water sample having $\delta^{18}O$ of –11.82 $^{o}/_{oo}$ was collected on 2/27/00, or 4 days after the recharge event began. For this well, the minimum vertical velocity is then greater than 70 ft/day.

The velocity calculation is also complex at city well 6 because samples from well 6 represent a composite of all water entering the well bore and because well 6 pumps continuously. The sample of –10.93 $^{o}/_{oo}$ $\delta^{18}O$ collected on 3/3/00 had a potential travel time of up to 9 days, and could have come from as shallow as 118 ft below the land surface. The minimum vertical velocity is then 13 ft/day, but it seems clear from the delay in arrival that the travel path might include significant horizontal movement.

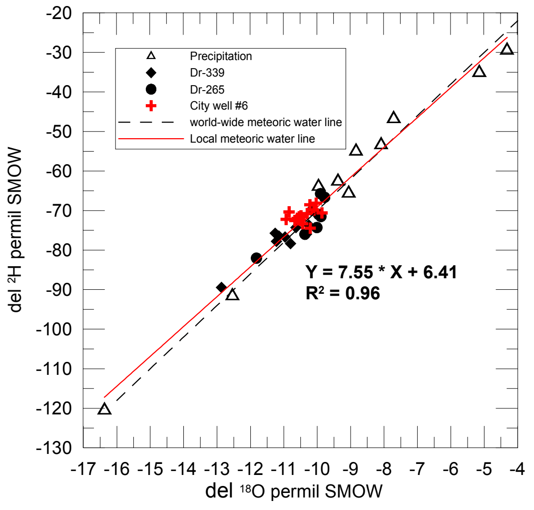

Figure 9. Plot of δ^2H vs δ ^{18}O from samples in the study area.

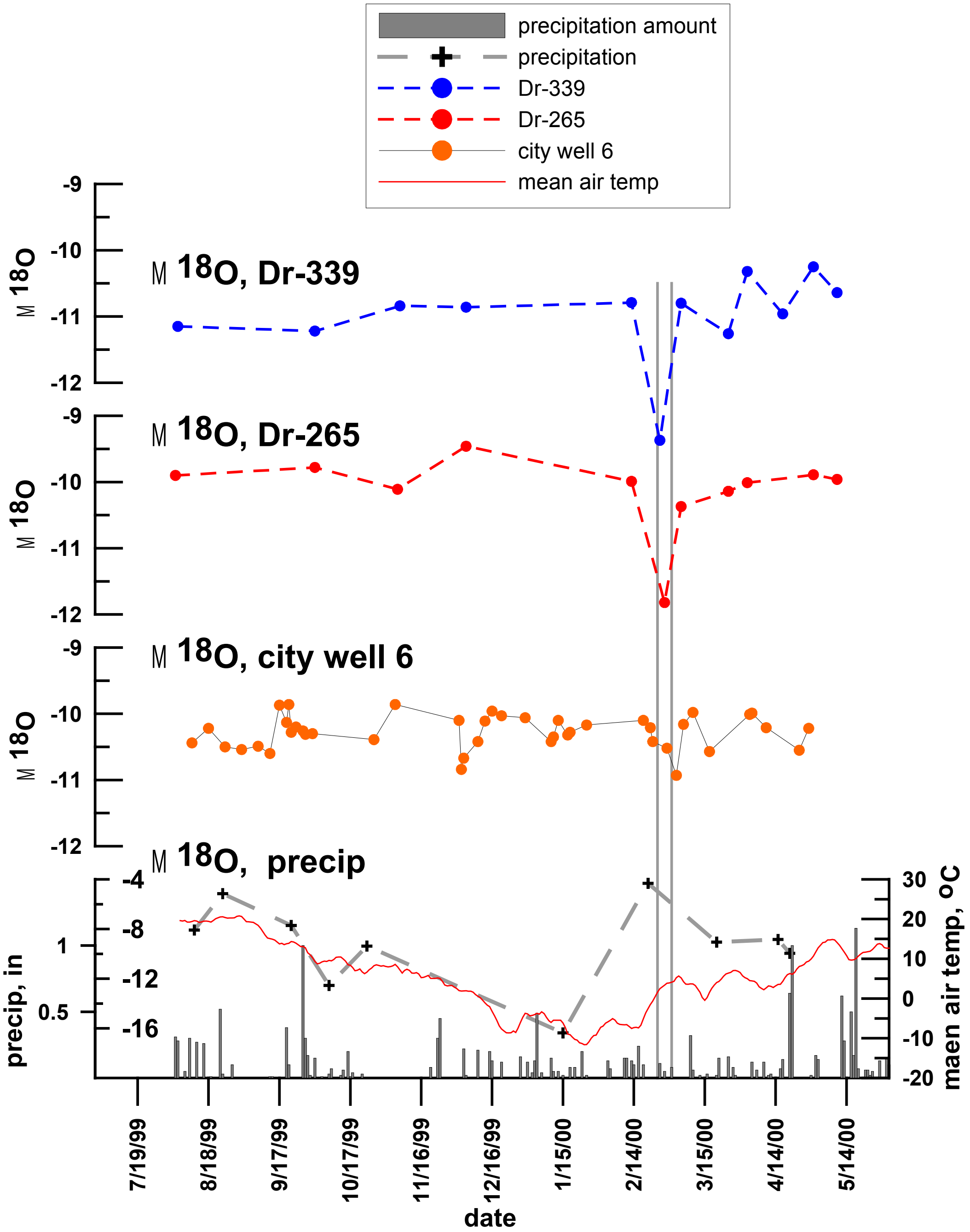

Figure 10. Variations of δ^{18}O, precipitation, and air temperature with time in the study area. Vertical lines bracket the late February recharge event.

Numerical Modeling

Background

The basis of the model for the Sturgeon Bay study includes the stratigraphic study of Gianniny and others (1996) and Muldoon and others (in press), and previous work by Bradbury and Muldoon (1992) and Sherrill (1978). The aquifer is composed of multiple, slightly dipping layers of dolomite, with an uppermost layer of unlithified material (sand and gravel, lacustrine deposits). The model simulates flow zones in the dolomite aquifer as thin, continuous, highly permeable layers. The intervals between the flow zones were modeled as thicker layers with lower horizontal and vertical hydraulic conductivities. Vertical fractures, which were not modeled discretely, control the flow between near-horizontal flow zones. The recharge rate is spatially variable, and is higher in areas where fractured dolomite is exposed and has undergone solution, or where soils are thin or absent.

Boundary conditions include specified head boundaries in Lake Michigan and Green Bay, head-dependent flux boundaries in Sturgeon Bay and streams in the model area, and no-flow boundaries at groundwater divides. The locations of groundwater divides were determined from the potentiometric surface maps from Bradbury and others (1998). Pumping rates for City of Sturgeon Bay municipal wells were averaged over a year to give temporally uniform withdrawal rates for each well.

The transient model was constructed to simulate the groundwater system through one water year, from October 1 through September 30. The model uses six stress periods that range in length from 30 to 150 days. Each stress period has different recharge rates, described in Bradbury and others (1998). Initial head conditions for the transient runs were taken from the calibrated steady-state model. Values of hydraulic conductivity and river node parameters from the steady-state model were used in the transient model. All parameter values are shown and discussed in Bradbury and others (1998).

Verification of the transient model

Groundwater temperature, conductivity, and isotope data collected during 1999 and 2000 indicate that the aquifer responds very rapidly to recharge events. Using these data, we attempted to test the transient model to determine if it responds in the rapid manner shown by the field measurements.

Methods

We used a particle-tracking code (MODPATH-3, Pollock [1994]) to simulate advection in the aquifer, based on the assumption that the parameters we monitored (temperature, conductivity, and stable isotopes) were conservative tracers, not subject to retardation or degradation. Imaginary particles of groundwater were placed in the recharge area of Municipal Well 6 and run forward in model time. In each particle-tracking run, 500 to

1000 particles were released at a time of low recharge rates (1 October) and a time of high recharge rates (1 March). The particles that were captured by the well were used to construct a "breakthrough" curve of number of particles versus travel time.

Results

The results of particle tracking in the model agree with the observed behavior of the aquifer. Simulated "breakthrough" curves at city well 6 of particles released at a time of low recharge rates (figure 11a) show the arrival of the "center of mass" (i.e. the mode of travel times) of the particles at about 40 days, compared to 8 days for particles released from the same location at a time of high recharge (figure 11b). This compares extremely favorably with the 9-day $\delta^{18}O$ breakthrough observed at city well 6 following the recharge event of late February, 2000. The rapid transport occurs because of substantially higher hydraulic gradients in the aquifer during times of high recharge. Figures 11a and 11b are the results of one particle tracking run with 775 particles released from approximately 5 km from Municipal Well 6. Results of other particle tracking runs show similar results – breakthrough occurs much sooner for particles released during times of high recharge. Note that the majority of the particles in this run were not captured by the well. This was typical in all model runs with forward particle tracking; most particles released in the upgradient areas in any specific model run discharge into Sturgeon Bay.

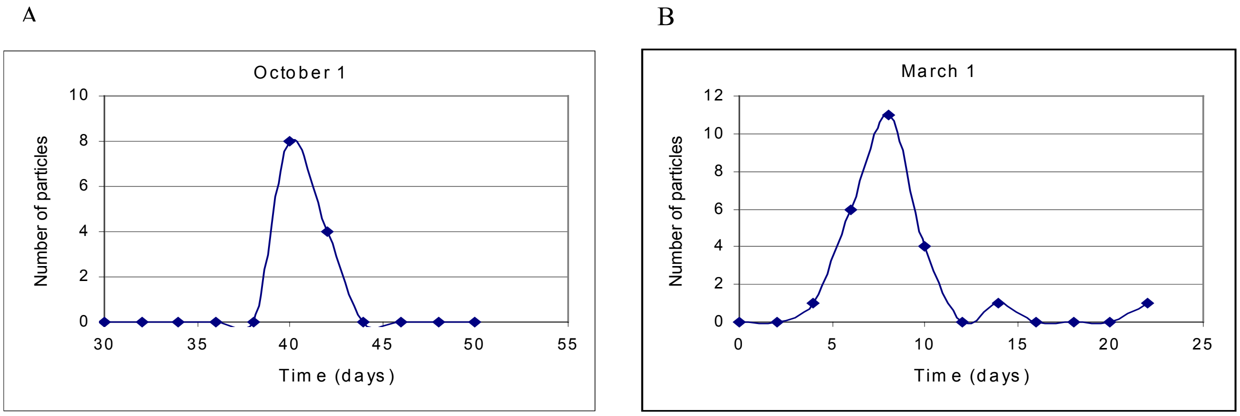

Figure 11. Model-simulated breakthrough curves for particles at city well 6, with particles released at the water table 5 km upgradient of the well. Particles were released in October (A) and March (B).

Conclusions and Recommendations

This study collected detailed temperature, fluid conductivity, and isotopic data at discrete points within a complex groundwater flow system in fractured dolomite near Sturgeon Bay, Wisconsin. The goals of the study were to improve our understanding of groundwater flow in this environment, to evaluate the use of natural groundwater tracers in wellhead protection studies, and to verify existing conceptual and numerical models of groundwater movement near Sturgeon Bay. The data collected have addressed all three of these goals and lead to conclusions in these three areas.

Groundwater movement near Sturgeon Bay

As reported in earlier studies (e.g. Bradbury and Muldoon, 1992), fractures control groundwater movement and recharge in central Door County, and groundwater velocities are extremely high. Minimum rates of vertical groundwater movement determined in this study range from 13 to 115 ft/day following recharge events, and may be significantly higher. Recharge is extremely episodic and variable, with most recharge occurring following snowmelt and large rainfall events in the early spring. Recharge occurs rapidly through vertical flow in central Door County. Recharge on the north side of the City of Sturgeon Bay is apparently less rapid although lateral transport through near-horizontal fracture zones occurs very rapidly.

The chemistry of groundwater in the study area responds rapidly to recharge events, and thermal, chemical, and isotopic signals are seasonally variable and detectable in the groundwater system. In particular, fluctuations in oxygen isotope ratios, measured in both monitoring wells and in the city production well, apparently correspond to seasonal recharge events. Based on the oxygen isotope data recharge water can appear in city well 6 in as little as 9 days after a recharge event.

Use of natural tracers in wellhead protection studies

Our results show that the use of “natural” tracers (temperature, fluid conductivity, oxygen and deuterium isotopes) can have great benefit in evaluating groundwater movement in fractured dolomite settings. Significant variations in all these parameters occurred through time and space during the study, and, in general, could be correlated with recharge events and/or with known subsurface fracture zones. These parameters are all easy and relatively inexpensive to measure and interpret. In particular, the continuous temperature/conductivity monitoring now possible with remote dataloggers provides an excellent and detailed record of recharge events for relatively low cost and minimal logistical effort. The $\delta^{18}O$ and $\delta^{2}H$ results show that $\delta^{18}O$ is a useful natural tracer in this environment and that fluctuations in $\delta^{18}O$ related to recharge events are traceable deep into the flow system and detectable in municipal wells. The sequential borehole logging is also extremely useful for detecting the transient influences of various fractures during recharge events and for evaluating groundwater mixing in the well bore. The one drawback to the data presented here is that the study period (1999-2000) proved to be unusually dry in Door County. Consequently, our data are probably not representative of a more typical year in which groundwater levels are higher and recharge events are more frequent and of higher duration.

Model verification

While the geochemical and isotopic data collected here cannot confirm the conceptual or numerical groundwater models near Sturgeon Bay they are consistent with the results of those models. Both the field study and the numerical model show that the dolomite aquifer responds very rapidly to recharge events. In the model, the simulated travel time from recharge to city well 6 is eight days during a high-recharge simulation. In the field, the $\delta^{18}O$ signal was detected at well 6 nine days after a major recharge event. In the monitoring wells, changes in the natural tracers occurred on the order of hours or days after a precipitation event. Even though natural tracers such as temperature, conductivity, and $\delta^{18}O$ cannot be 'released' from discrete points like particles in a model, the similarity in aquifer response and particle travel time suggests that the model is valid and the contributing areas delineated by the model are reasonable.

Recommendations

The analyses of the monitoring data collected during this study leads to several recommendations, as follows:

- We recommend that local officials continue to use the zones of contribution delineated by Bradbury and others (1998) for wellhead protection planning for Sturgeon Bay. The new field data collected in this study are consistent with the previous numerical modeling for the Sturgeon Bay municipal wells.
- The short-term variations in temperature and conductivity in deep monitoring wells and in the production well are additional evidence of the extreme sensitivity of groundwater in central Door County to contamination from surface sources. State and local officials and local residents should continue efforts to protect water quality in the dolomite aquifer by reducing or eliminating sources of contamination at the land surface.
- Continuous monitoring of electrical conductivity and temperature is a cost-effective way of characterizing temporal variability in groundwater quality in fractured-rock environments. Such instrumentation should be used routinely in fractured-rock characterization studies.
- Repeated downhole profiling of temperature and fluid conductivity in open boreholes is a relatively inexpensive method for characterizing the dynamics of regional fracture zones. Future studies should use such downhole profiling in combination with flow logging to quantify the exchange of water between fracture zones and boreholes.
- Variations in the stable isotopic ratios of oxygen and hydrogen in water can provide evidence of rapid recharge and estimates of groundwater flow rates in fractured carbonate settings. These isotopes can act as effective natural groundwater tracers and should be used routinely in groundwater studies in fractured carbonate rocks.

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