Recharge Processes in an Alluvial Aquifer Riparian Zone, Norman Landfill, Norman, Oklahoma, 1998–2000

Scientific Investigations Report 2004–5238

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

Cover: Photo of the riparian zone, sandy alluvium, and slough at the Norman Landfill, Norman Oklahoma, taken by Scott Christenson, U.S. Geological Survey.

Scholl, Martha and others.—Recharge Processes in an Alluvial Aquifer Riparian Zone, Norman Landfill, Norman, Oklahoma, 1998-2000—USGS/SIR 2004–5238

Printed on recycled paper

Recharge Processes in an Alluvial Aquifer Riparian Zone, Norman Landfill, Norman, Oklahoma, 1998–2000

By Martha Scholl, Scott Christenson, Isabelle Cozzarelli, Dale Ferree,
and Jeanne Jaeschke

Scientific Investigations Report 2004–5238

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

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Reston, Virginia
For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

District Chief
U.S. Geological Survey
202 NW 66 St., Bldg. 7
Oklahoma City, OK 73116

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: http://www.usgs.gov/

Information about water resources in Oklahoma is available on the World Wide Web at
http://ok.water.usgs.gov

UNITED STATES GOVERNMENT PRINTING OFFICE: OKLAHOMA CITY 2005

Contents

Figures

Figures 5–8. Graphs showing:

Tables

Conversion Factors and Datum

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
inch (in.)	2.54	centimeter (cm)
Volume		
liter (L)	33.82	ounce, fluid (fl. oz)
milliliter (mL)	0.0338	ounce, fluid (fl. oz)
Flow rate		
centimeter per year (cm/yr)	0.3977	inch per year (in/yr)
millimeter per day (mm/d)	0.03937	inch per day (in/d)
milliliter per minute (mL/min)	0.0338	ounce per minute (oz/min)

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

°F = (1.8 × °C) + 32

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

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

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

NOTE TO USGS USERS: Use of liter (L) as a special name for cubic decimeter (dm^3) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter.

Recharge Processes in an Alluvial Aquifer Riparian Zone, Norman Landfill, Norman, Oklahoma, 1998 - 2000

By Martha Scholl, Scott Christenson, Isabelle Cozzarelli, Dale Ferree, and Jeanne Jaeschke

Abstract

Analyses of stable isotope profiles (δ^2H and $\delta^{18}O$) in the saturated zone, combined with water-table fluctuations, gave a comprehensive picture of recharge processes in an alluvial aquifer riparian zone. At the Norman Landfill U.S. Geological Survey Toxic Substances Hydrology research site in Norman, Oklahoma, recharge to the aquifer appears to drive biodegradation, contributing fresh supplies of electron acceptors for the attenuation of leachate compounds from the landfill. Quantifying recharge is a first step in studying this process in detail. Both chemical and physical methods were used to estimate recharge. Chemical methods included measuring the increase in recharge water in the saturated zone, as defined by isotopic signature, specific conductance or chloride measurements; and infiltration rate estimates using storm event isotopic signatures. Physical methods included measurement of water-table rise after individual rain events and on an approximately monthly time scale. Evapotranspiration rates were estimated using diurnal water-table fluctuations; outflux of water from the alluvial aquifer during the growing season had a large effect on net recharge at the site.

Evaporation and methanogenesis gave unique isotopic signatures to different sources of water at the site, allowing the distinction of recharge using the offset of the isotopic signature from the local meteoric water line. The downward movement of water from large, isotopically depleted rain events in the saturated zone yielded recharge rate estimates (2.2 - 3.3 mm/day), and rates also were determined by observing changes in thickness of the layer of infiltrated recharge water at the top of the saturated zone (1.5 - 1.6 mm/day). Recharge measured over 2 years (1998-2000) in two locations at the site averaged 37 percent of rainfall, however, part of this water had only a short residence time in the aquifer. Isotopes showed recharge water entering the ground-water system in winter and spring, then being removed during the growing season by phreatophyte transpiration. Recharge timing was variable over the course of the study; July and August were the only months that had no recharge in both years. Recharge to the aquifer from the slough (wetland pond) was estimated at one location using the isotopic signature of water affected by evaporation. Recharge was correlated with the rainfall amount over the period of estimation, suggesting that recharge from the slough to the downgradient aquifer was an episodic process, corresponding to elevated water levels in the slough after large rain events.

Introduction

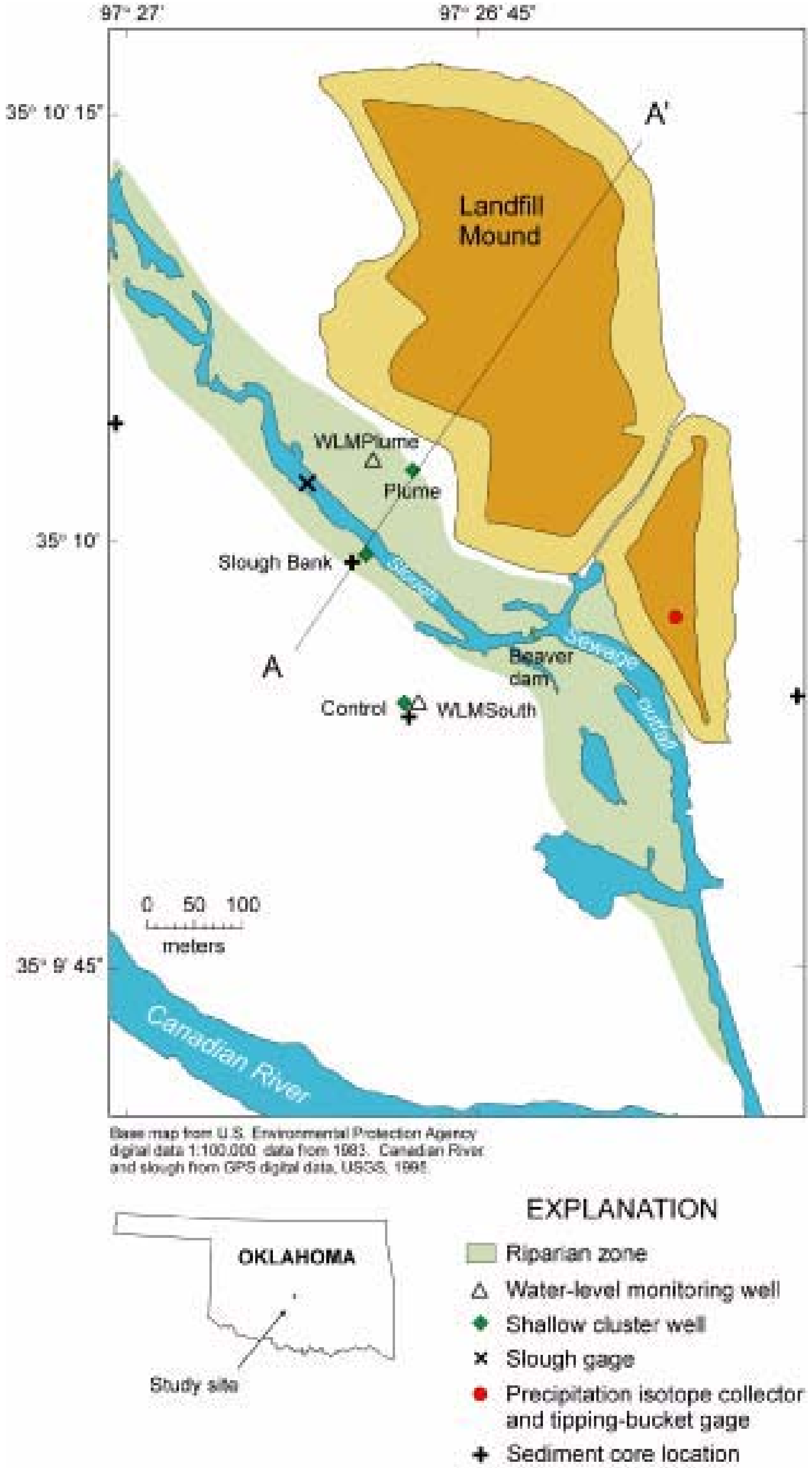
A municipal landfill on the alluvial plain of the Canadian River in Norman, Oklahoma, accepted solid waste from 1922 to 1985, when it was closed and capped with a clayey soil (fig. 1). The landfill was unlined, and a leachate plume extends at least 225 meters (m) downgradient in the unconfined, 12-m thick alluvial aquifer. The landfill is one of the U.S. Geological Survey Toxic Substances Hydrology Program study sites (Christenson and Cozzarelli, 2003).

The overall objectives of research at the site are to understand the biogeochemical and hydrological processes that affect the fate and transport of contaminants in the leachate. The landfill leachate plume within the aquifer has several different zones in which biodegradation of leachate compounds may occur (Cozzarelli and others, 2000); of particular interest are two areas where recharge is entering the anaerobic aquifer. These areas are the top of the saturated zone between the landfill and the slough, and in the upper part of the aquifer downgradient from the slough (fig. 2). The influx of recharge has been hypothesized to cause oxidation of sulfides and iron near the water table, providing a fresh source of electron acceptors that may stimulate biological activity (Ulrich and others, 2003). This study covered the 2-year period from May 1998 to May 2000. The objective of this study was to quantify the amount and timing of recharge to the alluvial aquifer from rainfall and from the slough.

Description of Norman Landfill Area

Annual precipitation at the site is approximately 96 centimeters per year (cm/year), and precipitation occurs year round. May and June have the most rainfall, with a secondary maximum in September and October (National Oceanic and Atmospheric Administration - National Weather Service, 2003). The growing season is from mid-April through October.

The aquifer material is predominantly fine to medium grained sand with intermittent mud layers and lenses (Marston and others, 2001). The area near the landfill is densely vegetated, with at least three species of phreatophytes— willow, cot-



Base map from U.S. Environmental Protection Agency digital data 1:100,000 data from 1983. Canadian River and slough from GPS digital data, USGS, 1998

Figure 1. Location of the Norman Landfill, Norman, Oklahoma, showing the vegetated riparian zone, slough, water level monitoring wells and multi-level cluster wells. The transect A–A' is shown in cross section in figure 2.

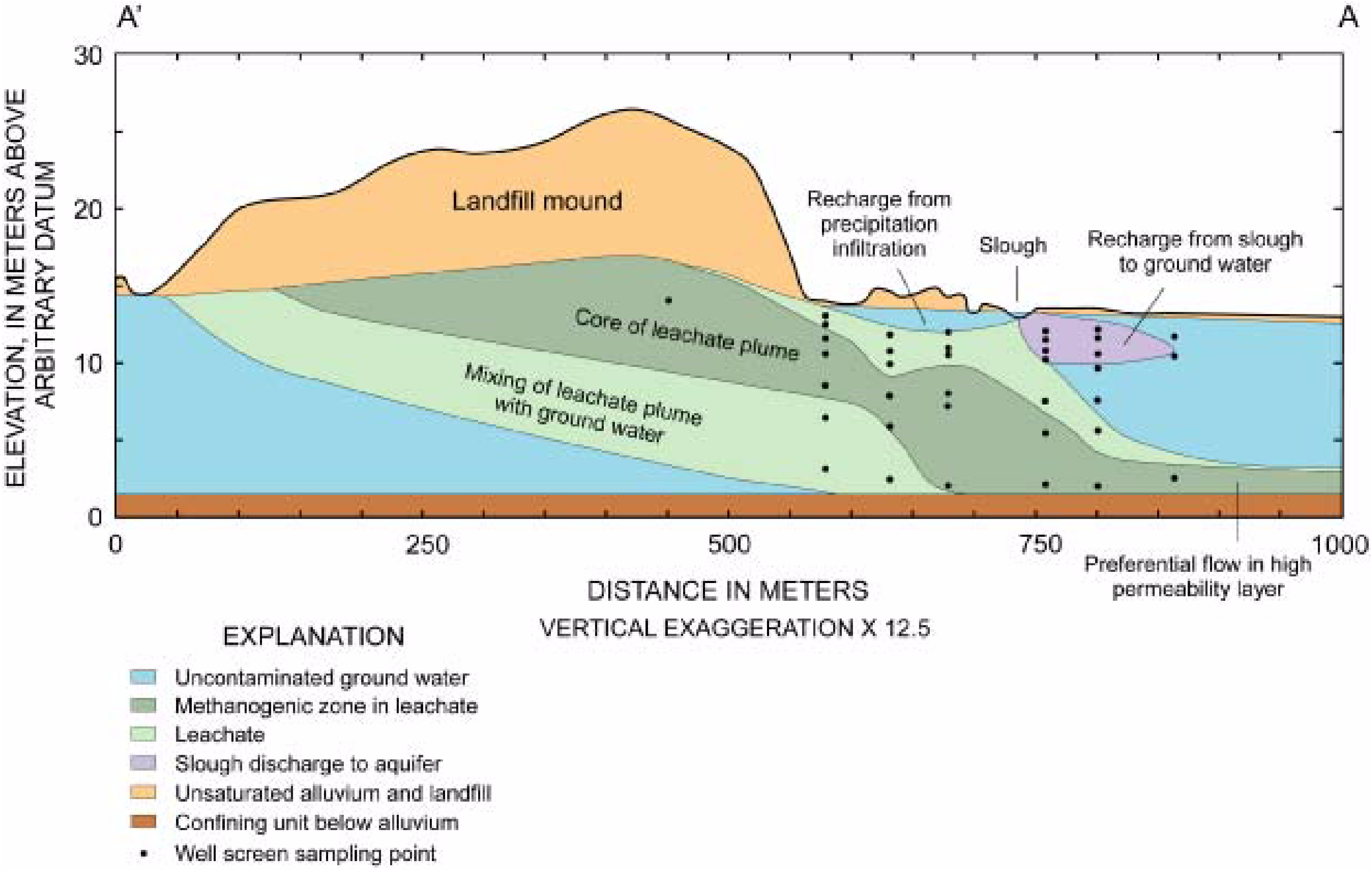


Figure 2. Cross-sectional view of the Norman Landfill, Norman, Oklahoma. Line of section shown in figure 1. The leachate plume and recharge zones within the aquifer are a composite, drawn on the basis of chemistry measurements made in the ground-water at the sampling locations shown, from 1997 to 2002 (those data are not included in this report.)

tonwood, and tamarisk (salt cedar) (Christenson and others, 1999). There is a slough (wetland pond) impounded by a beaver dam in a former channel of the Canadian River; the slough is approximately 700 m long and 15-25 m wide, and is 50-100 m from the edge of the landfill (fig. 1). The slough is downgradient from the landfill and functions as a surface expression of the local water table. It has some lateral flow; input from upstream and seepage through the beaver dam to a nearby sewage outfall stream are observed. The slough was dry for a period during both summers of 1998 and 1999 when the water table dropped below the slough bottom.

The leachate plume extends from the southern edge of the landfill at least 225 m downgradient in the direction of the Canadian River and fills almost the entire 12 m thickness of the alluvium in the area between the landfill and the slough (fig. 2). The leachate emanating from the landfill sinks to the bottom of the aquifer as distance from the landfill increases, due to a high-permeability layer at the bottom of the alluvium. Samples from a multi-level well transect parallel to the flow direction have allowed delineation of different biogeochemical zones within the leachate plume (Cozzarelli and others, 2000). The layer of infiltrated recharge water above the leachate plume between the landfill and the slough and the water entering the aquifer from the slough can be discerned on the basis of chemistry, with sulfate concentration and isotopic composition (δ^2H or δ^{18}O) being the most specific parameters.

Water-level fluctuations in monitoring wells show daily and seasonal changes. Ground-water levels in the wells used in this study change by as much as 1.4 m from winter to summer, rise rapidly in response to rainfall events, and diurnal fluctuations indicate transpiration processes are the dominant cause of water-level decline during the growing season (fig. 3). The depth of the water table below land surface (thickness of the unsaturated zone) ranged from 0.24 to 1.72 m during the study. The water level rises to a peak within 0.6-2 days after the start of precipitation, and decreases over about 4 to 15 days, depending on season and amount of recharge.

Previous Investigations

Methods for determining recharge using water-level fluctuations have been used at many sites with shallow, unconfined aquifers (Healy and Cook, 2002). There are several sources of uncertainty associated with using these methods, with probably the largest being the specific yield (S_y). Specific yield varies with the height of the water table, the grain size distribution of the aquifer materials, and time (Sophocleous, 1985, Healy and Cook, 2002, Nachabe, 2002). Uncertainty is also introduced by the fact that water-level rise is not always due to water from the unsaturated zone entering the saturated zone. Pressure effects from rain falling on the land surface over a relatively dry unsaturated zone can cause temporary water-level rises (the Lisse effect, see Weeks, 2002), and lateral flow can cause rises in the water table that are not due to infiltration.

Many studies have used ^{18}O and ^{2}H in rainfall to estimate residence time for various types of water in catchments including soil water, streamflow, and shallow ground water (McGuire and others, 2002; Turner and Barnes, 1998; Vitvar and Balderer, 1997; Stewart and McDonnell, 1991). Most of these studies relied on a predictable seasonal variation of isotopic composition in precipitation to model the isotopic content of the infiltrating precipitation. Even in areas where the seasonal variation is distinct, there are difficulties interpreting residence times due to mixing processes in the unsaturated zone and mixing of new recharge with older ground water (McGuire and others, 2002). Other studies have successfully used stable isotopes to quantify timing or amounts of ground-water recharge from different sources, for example in a contaminant plume (Bohlke and others, 1999) and an alluvial plain (Guglielmi and Mudry, 1996).

A recharge study done in Kansas, in an area climatologically similar to the Norman site, found that two instrumented sites varied dramatically in the amounts of recharge that reached the saturated zone. The factors that determined recharge were the thickness of the unsaturated zone and antecedent moisture conditions, related to evapotranspiration (ET) and precipitation differences. Recharge occurred only during the late winter and spring, with no recharge in summer or fall (Sophocleous and Perry, 1985).

Purpose and Scope

The purpose of this report is to provide a comparison of several different methods for determining recharge, including water-level fluctuations and isotope tracer methods. The importance of recharge as a supply of electron acceptors for biodegradation of a contaminant plume in a shallow unconsolidated aquifer is investigated. The report describes in detail recharge processes in a riparian zone; recharge in these zones has not been studied much, as they are generally thought of as discharge areas.

The hydrologic system at the landfill is dynamic, with the water table close to the surface and large seasonal variations in water level due to transpiration. The zero-flux plane concept, that recharge includes all water that infiltrates below the root zone, is not applicable here in the traditional sense, because the vegetation community uses water from both the unsaturated and saturated zones. Infiltrated water that reaches the saturated zone may only be in the aquifer a short time (days) before being removed by transpiration.

Healy and Cook (2002) noted that it is best to use multiple methods to estimate recharge at a site, as it is difficult to assess the accuracy of any particular method. That approach is taken in this study, where several methods were used to quantify recharge at the site. Differences in water levels measured in wells were used on both an event basis and between sampling periods (about monthly) to estimate recharge. Evaporation from the slough and methanogenesis in the leachate plume lend distinctive isotopic signatures to the different water types at the

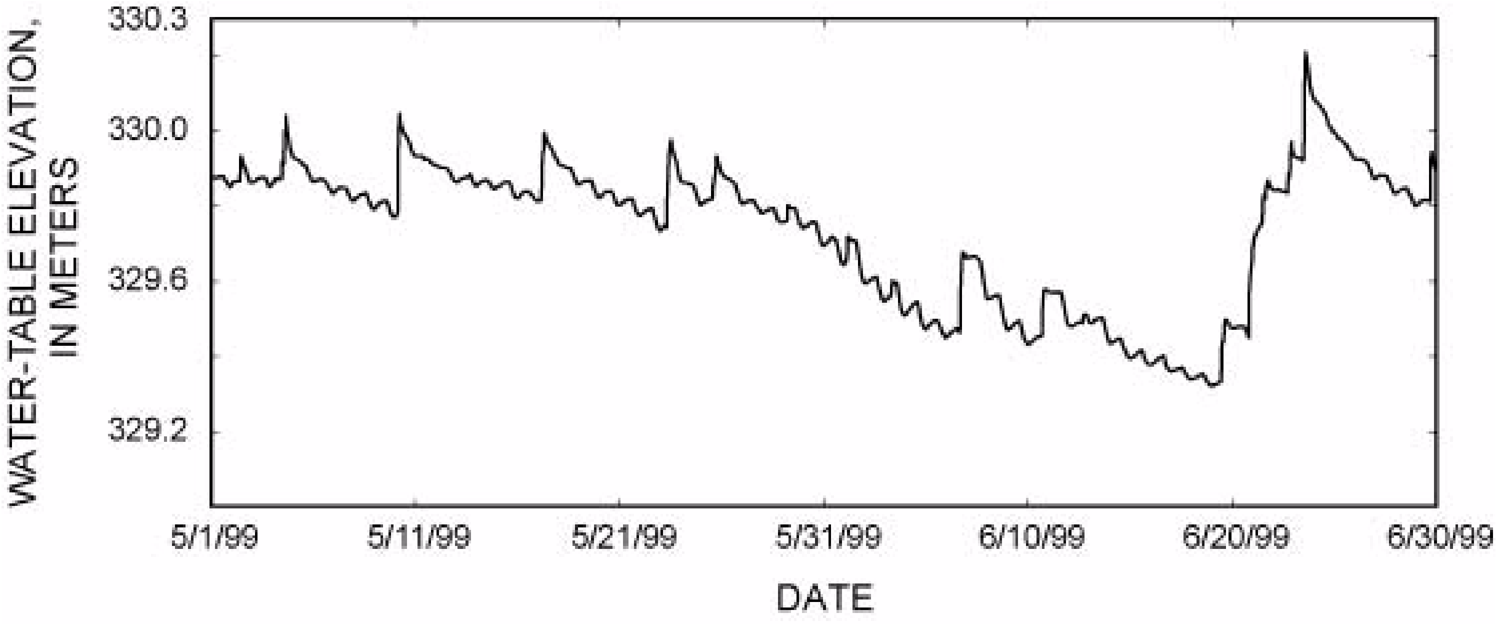


Figure 3. Water-level record for the Control site at the Norman Landfill, Norman, Oklahoma, May–June 1999, showing typical fluctuations from rain events and transpiration. Water-table elevation is in meters based on the North American Vertical Datum of 1988. The top boundary of the plot is the land-surface elevation at 330.3 meters.

site, allowing distinction of infiltrated recharge water from the underlying ground water. Recharge rates were estimated by observing changes in thickness of the layer of infiltrated recharge water, and rain events with distinct isotopic signatures were tracked during the infiltration process to yield rate estimates. A detailed picture of the timing and type of rain events that contribute to recharge, as well as the residence time of recharge in the system, was obtained. With these estimates of recharge, further work can be done to determine the importance of the interface between recharge zones and contaminant plumes in biodegradation of contaminants.

Acknowledgments

The authors thank the personnel of the USGS Reston Stable Isotope Laboratory for their careful analysis of the isotope samples. Ludmilla Aristilde (Cornell University) helped with the ET analyses. Richard Healy (USGS) analyzed the sediment cores for the study. James LaBaugh (USGS) and Richard Healy improved the report with their technical reviews. The authors thank Lyn Osburn and Barbara Cardellichio (both at USGS) for their help in preparing the final report for publication.

Sampling Methods for Precipitation, Ground Water, and Slough Water

Precipitation for stable isotope analysis was collected biweekly in a funnel/bottle collector containing a 1-centimeter (cm) layer of mineral oil to prevent evaporation. The funnel was 17.4 cm in diameter, inserted through a stopper in a 2-liter (L) collection bottle. Samples for isotopic analysis were poured through a separatory funnel to remove mineral oil from the sample, into 60 milliliter (mL) glass bottles with polyseal caps. The volume in the precipitation isotope collector was measured with a graduated cylinder. There were a few periods that the bottle overfilled so either no analysis was done or the analysis represents only part of the rainfall for the 2-week period. Precipitation amounts were measured at the weather station on top of the landfill mound with a standard 8-inch tipping-bucket rain gage (University of Oklahoma Mesonet, unpub. data, May 1, 1998, through May 31, 2000). Precipitation isotope analysis began in May 1996, 2 years before the recharge study began, and is ongoing (August 2004). The precipitation isotope values for the period May 1996 through May 2000 are given in appendix 1.

Water levels were continuously monitored at eight locations at the site, using down-well vented pressure transducer/data logger instruments. Data from three locations closest to the study sites were used in this analysis: 1) WLMPlume, located downgradient from the landfill; 2) WLMSouth, located on the alluvial plain south of the landfill and wetland; and 3) Slough Gage, a stage recorder in the slough (fig. 1). Water levels recorded by the pressure transducers were checked at least monthly using an electronic water level tape.

The shallow ground water was sampled at time intervals ranging from 9 to 55 days, but usually once per month. In this report, the term "shallow ground water," when used in reference to the Norman Landfill site, means ground water at depths of less than 5 meters from the land surface; and the term "monthly," when used in the context of ground-water measurements, refers to the time between ground-water sampling periods. Ground water was sampled in three cluster wells (figs. 1 and 4). Each cluster had 15-17 wells of 18-millimeter (mm) inside-diameter PVC pipe with 16-cm slotted screens. The cluster well sites were: 1) Plume (IC36), located 35 m from the edge of the landfill, where the leachate plume is about 2 m below the land surface and is overlain by a thin layer of uncontaminated water; 2) Slough Bank (IC54), located 7 m from the downgradient edge of the slough, where water from the slough enters the aquifer and overlies the leachate plume; and 3) Control (ICSouth), located on the alluvial plain 85 m downgradient from the slough, meant to be a control site with no influence from the slough or the leachate plume.

Specific conductance, stable isotope, and anion (chloride is reported in this report) samples were taken from the top of the saturated zone and at each successive depth until the bottom of the well cluster was reached. The volume of standing water in each cluster well was calculated on the basis of the water level measured that day. The intake for the peristaltic pump was placed at the water table, and moved down while pumping at a relatively fast rate to evacuate the calculated volume of standing water. Because the well volume was small, the standing water was completely evacuated from the well before sampling. Samples were then taken with the pump intake at the screen, using a relatively slow flow rate (about 30 mL/minute) to avoid pulling water from other levels of the aquifer. Samples were taken approximately monthly, from May 1998 to May 2000 at the Slough Bank and Control sites. The first well installed at the Plume site in May 1998 did not function properly. Sample collection at a new well began October 1998 and ended May 2000, so the data record for the Plume site is shorter than for the other two sites.

The slough samples were taken at a location directly north of the Slough Bank well, by wading to the middle of the slough and using a bailer to obtain a depth-averaged sample of the water column. If this part of the slough was dry during the late summer, water remaining near the gage at the deepest part of the slough was sampled.

Specific conductance was measured at the time of sampling. Anion samples were filtered through a 0.45-micrometer filter into 30-ml high-density polyethylene (HDPE) bottles that were rinsed twice with filtered water, and refrigerated until analysis. Anions were analyzed on a Dionex ion chromatograph. Isotope samples were taken unfiltered in unrinsed 60-mL glass bottles with polyseal caps. All isotope samples were analyzed in the USGS Reston Stable Isotope Laboratory. Oxygen and hydrogen isotopic results are reported in per mil (‰) relative to Vienna Standard Mean Ocean Water (VSMOW) and normalized on scales such that the oxygen and hydrogen iso-

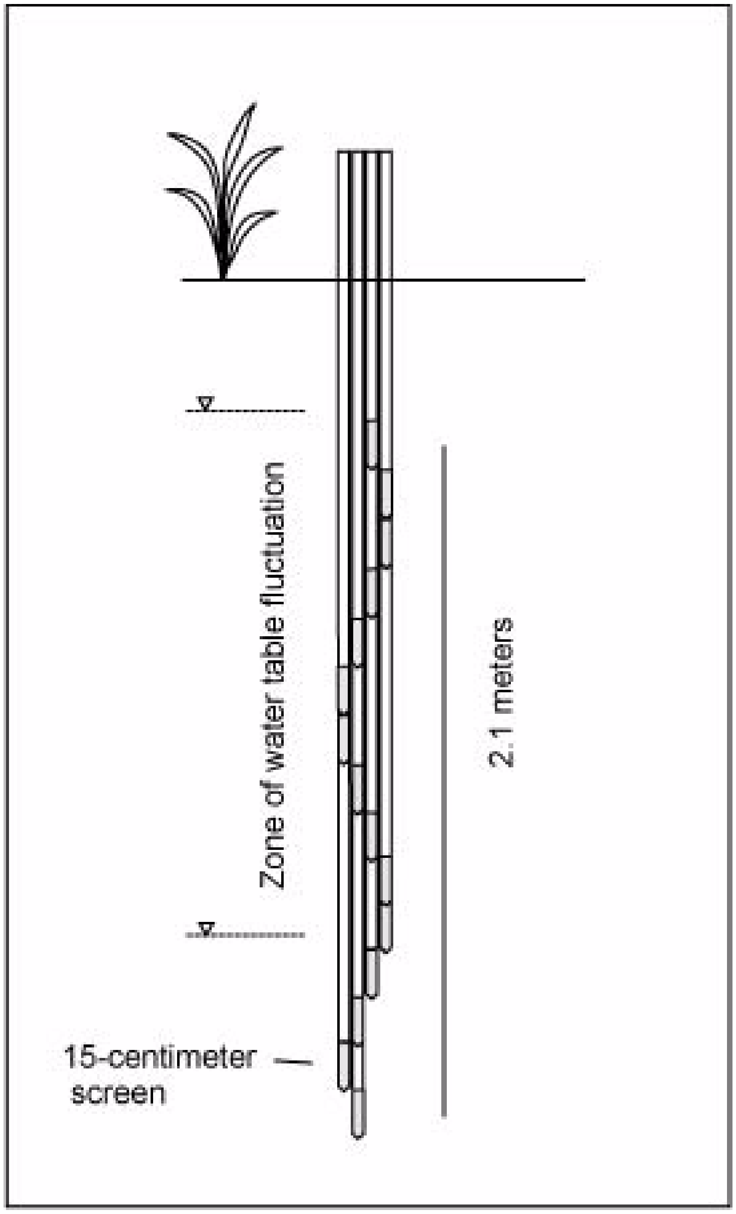


Figure 4. Diagram of the multi-level cluster wells used to obtain samples for profiles of isotopic composition and chemistry in the shallow aquifer at the Norman Landfill. Each well screen is 15 centimeters long, and the screens are placed adjacent to one another so a depth interval of about 2 meters is covered.

topic values of Standard Light Antarctic Precipitation (SLAP) are -55.5 ‰ and -428 ‰, respectively. Deuterium (δ^2H) analyses of the water samples were done by equilibration with gaseous hydrogen and automated analysis; precision is around ± 1 ‰. Oxygen-18 ($\delta^{18}O$) analyses were done by equilibration with carbon dioxide and automated analysis; precision is around ± 0.1 ‰.

Recharge and Evapotranspiration Estimates

Determination of Specific Yield

Specific yield is the parameter needed in all determinations of recharge by water-level fluctuations or identification of infiltrated water using chemical methods. Two methods to determine S_y were used in this study, a field method using water table rise after rainfall, and a laboratory method using sediment cores.

Water-level fluctuations

For the field determination of S_y, over the 2-year period of study, selected rain events were correlated with water level rise in two of the monitoring wells. The water-level records for WLMPlume, located near Plume, and WLMSouth, located at the same site as Control, were used. Water levels were recorded at 30 or 60-minute intervals, and the rainfall record from the weather station was condensed to daily totals. A spreadsheet program was written that identified all rising portions of the water-level record within each 6-hour period, then added the rises to obtain total rise for each day. There were 98 rain events with amounts ranging from 0.5 to 125 mm (0.02 to 4.94 inches) in the 2-year period, with a rain event defined as one or more consecutive days with rainfall ≥ 0.02 inch. Water-level rises for each rain event were totaled, and then rainfall was plotted against rise. The water-level rise in response to the rainfall varied with season; water table rise with rainfall was generally smaller during the growing season. Some rain events produced no change in the water table; most of these events were in the spring and summer months. This result was consistent with large water outflux from both the unsaturated and saturated zones due to transpiration.

To make a field-data-based estimate of S_y, water table rises that occurred under wet conditions were selected and the relation

$$S_y = (\text{Precipitation} / \text{Water-level rise})$$

was used (Rosenberry and Winter, 1997; Gerhart, 1986; Rasmussen and Andreasen, 1959). For this estimate, evapotranspiration (ET), interception by vegetation, and runoff were assumed to be negligible and all of the rainwater entered the unsaturated zone and displaced an equal amount of water to the saturated zone. Rain events that were no more than 2 weeks after a previous event were selected, and only events from November-June were included, as transpiration had a substantial effect on local water levels during July-October. For the measurements that were used, the water table at Control (WLM South) was 0.5-1 m below land surface, whereas the water table at WLM Plume was generally 1.0-1.4 m below land surface. Total rainfall amount was plotted against water-level rise for each rain event, and a linear regression was fit to the data set for all rain events. The slope of the regression for each site was taken as the estimate of S_y for the site. Values were similar: 0.12 and 0.10 for the Plume and Control sites, respectively (fig. 5), however, there was a larger rise in water table at the Control site than at the Plume site for each rain event. There also was a disproportionately large rise in water level for the smallest rain events at the Control site. The reason for this disproportionate rise is unknown; but it is likely that water levels at the Control site were affected by the response of the slough and/or the nearby sewage outfall (fig. 1) to rainfall. During a period of repairs at the local sewage treatment plant, discharge of treated sewage was stopped and started daily; this action caused water-level fluctuations of 0.2-0.4 m in the Control well.

Laboratory tests on cores

Trenches were excavated to the saturated zone at four locations using a track hoe, in order to collect cores in the zone of water-table fluctuation (fig. 1). Coring was done in August when the water table was lowest and the unsaturated zone was relatively dry. Cores 5 cm long and 4 cm in diameter were taken at three depths in the unsaturated zone using brass cylinders that were pressed into the sand, which was smoothed prior to coring. Cores were analyzed for porosity, moisture content and moisture retention using methods in Klute (1986). The S_y was calculated by subtracting the residual moisture under 50 cm pressure from the porosity (Richard Healy, U.S. Geological Survey, oral commun., 2003). Porosity for the cores ranged from 0.34 to 0.44. The S_y values ranged from 0.19 to 0.29, with an average of 0.23 (table 1).

The actual S_y of aquifer sediment is not constant in time or space. The S_y depends on the capillary fringe above the water table, the depth of the water table below land surface, inhomogeneity of the sediments, the size of the change in water level, whether the water table is rising or falling, and the time allowed for the aquifer system to reach equilibrium (Duke, 1972; Nachabe, 2002). For short-term excursions of the water table, such as transpiration estimates and estimates of recharge from individual rain events, the field-derived S_y value of 0.11 was used. The laboratory-derived S_y value of 0.23 was used for recharge estimates from monthly measurements of the infiltrated recharge layer and net water table rise, because the aquifer system generally had time to approach equilibrium between sampling periods (described below). Overall recharge estimates are presented using S_y values from both laboratory and field estimates, as the actual value of S_y for the aquifer depends on several factors, and is probably between the two values.

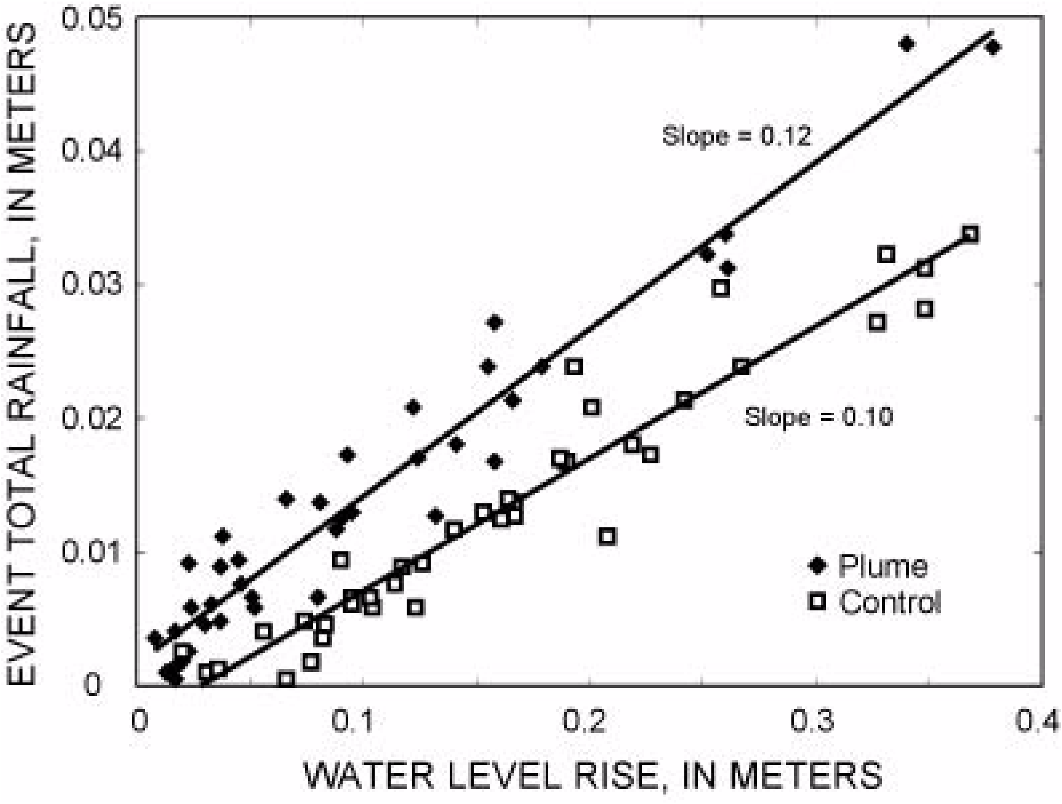


Figure 5. Water-level rise with rainfall for selected rain events at the Plume and Control sites at the Norman Landfill, Norman, Oklahoma. All events were less than 2 weeks after previous rainfall and rain events during the growing season were excluded. The field-derived value for specific yield is the slope of the rainfall/water-level rise regression line.

Table 1. Parameters obtained from analysis of sediments from the alluvial aquifer at Norman Landfill, Norman, Oklahoma.

[cm, centimeters; <, less than]

	Range of values	Average value	Number of samples
Porosity	0.34 - 0.44	0.40	12
Specific yield	0.19 - 0.29	0.23	9
Air entry pressure head, cm	<1 - 30	[1]25	10
Pore size distribution index	2.35 - 3.52	2.78	9

[1] Median value

Nachabe (2002) presents expressions for the change in S_y with depth to water table and with time. The S_y approaches its ultimate value as depth to water table increases and as time increases. The average laboratory-derived value of 0.23 is assumed to be the ultimate S_y for the study area. To determine which S_y value was appropriate for the longer-term monthly recharge estimates, an average depth to water table of 1 m and representative field values of hydraulic conductivity near the Plume and Control sites (Scholl and Christenson, 1998) were used to calculate the time to reach the ultimate S_y (Nachabe, 2002, eq. 14). These times ranged from 34 to 57 days, so for processes on a shorter time scale, the S_y value would be less than 0.23. At the Norman site, water table rise after rain events occurred in 14-48 hours, so the field derived S_y value of 0.11 is in agreement with the assumption of a non-equilibrium condition. The 0.23 value of S_y was used for the monthly recharge estimates; however, actual recharge amounts may be slightly less than calculated, depending on the departure of actual conditions from the average parameters used for the equilibration time estimates.

Evapotranspiration Estimates

Evapotranspiration was estimated with water-level fluctuations using the method of White (1932) as described in Meyboom (1967). This method can be used where there are clear diurnal variations in ground-water level in periods without rainfall. The daily cycle of water-level decline during daylight hours and recovery of water levels at night is used to determine the amount of uptake by the transpiring plants, using the relation

$$q = S_y (24r \pm s),$$

where q is the depth of water withdrawal (L),

S_y is specific yield (dimensionless),

r is hourly rate of ground-water inflow (L/T, from the rate of rise at night), and

s is the net rise or fall of the water table during the 24-hour period (L).

Daily transpiration estimates were made on all suitable parts of the hydrograph for the Plume and Control monitoring wells during the growing seasons of 1998-99. Transpiration could be accurately measured between rain events, after the recession of peak water levels. The S_y used to estimate transpiration was corrected for depth of the water table below land surface, using equation (7) from Duke (1972). The parameters needed for this assessment include the air-entry pressure and the pore-size distribution index, which were estimated from plots of capillary pressure head versus effective saturation using pressure cell data from the core samples (table 1). The average values from all samples that had pressure cell data were used. The calculated S_y values using Duke's expression decrease as the water table approaches the land surface. As the field-observed S_y was calculated on a similar time scale and range of depths to water table as the ET fluctuations, it is a more appropriate value to use than the laboratory value. Therefore, the ultimate S_y value was set at 0.11 and corrected for depth to water table by Duke's expression. The range of S_y was small, from 0.094 at 0.5 m depth to 0.11 at 2 m depth. These values were used to calculate ET depending on the baseline water level at the time they were measured.

At the Control site, each summer had similar patterns. Diurnal fluctuations began in April, with relatively large-amplitude fluctuations (see figure 3 for example of fluctuations). By August, water levels in the aquifer had declined as much as 1.2 m, and diurnal fluctuations were smaller in amplitude. Fluctuations were not discernable after the beginning of October. Changes in ground-water levels at the Plume site were similar to the Control site, but diurnal fluctuations were smaller, so that measurable fluctuations started later in the season, and ended earlier. There are several possible reasons for the different patterns: the sediments may be different; the Plume site ground water is predominantly landfill leachate, which may affect plant health; and there are mature cottonwoods and willows at the Plume site, whereas the trees at the Control site are saplings. At the San Pedro River riparian zone study site in Arizona (Snyder and Williams, 2000), willows used only ground water while cottonwoods used both soil water and ground water, so differences in numbers of those species may be important. The decreasing amplitude of transpiration fluctuations with water table decline at Norman Landfill may be due to a lower density of roots with increasing depth to the water table. Isotopic profiles from 1999 and 2000 (appendix 2, figs. 2-12, 2-13, 2-19 and 2-20) show that as the growing season proceeded, water was removed from the water table downward, with the most recent (early summer and spring) rain events removed first.

Calculated ET rates for the Plume site ranged from 1.6 to 9.3 millimeters per day (mm/day), with an average of 4.0 mm/day. For the Control site, ET ranged from 2.5 to 13 mm/day, with an average of 5.3 mm/day. For comparison, transpiration (only) rates estimated using sap flux measurements from a cottonwood/willow forest near the San Pedro River in southeastern Arizona averaged 4.8 mm/day, with a range of 3.1 to 5.7 mm/day (Schaeffer and others, 2000). ET rates from a shallow aquifer in North Dakota, estimated by the same water table fluctuation method, averaged 3 to 7 mm/day, based on a range of values from 1 to 9 mm/day (Rosenberry and Winter, 1997). ET rates estimated by various methods, including water table fluctuation, in a natural wetland in Wisconsin averaged 3.6 mm/day, with a range of 1.9 to 8.7 mm/day (Lott and Hunt, 2001). Average ET rates estimated from weather station data at the Norman Landfill for May-June 1997 were 2.4 to 5.8 mm/day using various methods (Gossard and others, 1998); however, in their calculations, potential evapotranspiration (PET) rates were adjusted using soil moisture data to obtain ET rates. Soil moisture may not be relevant in phreatophyte transpiration, so their ET estimates for this site may be low.

Evapotranspiration rates varied with changes in water level at both the Plume (fig. 6A) and Control (fig. 6B) sites. The higher values for ET at the Control site may not be accu-

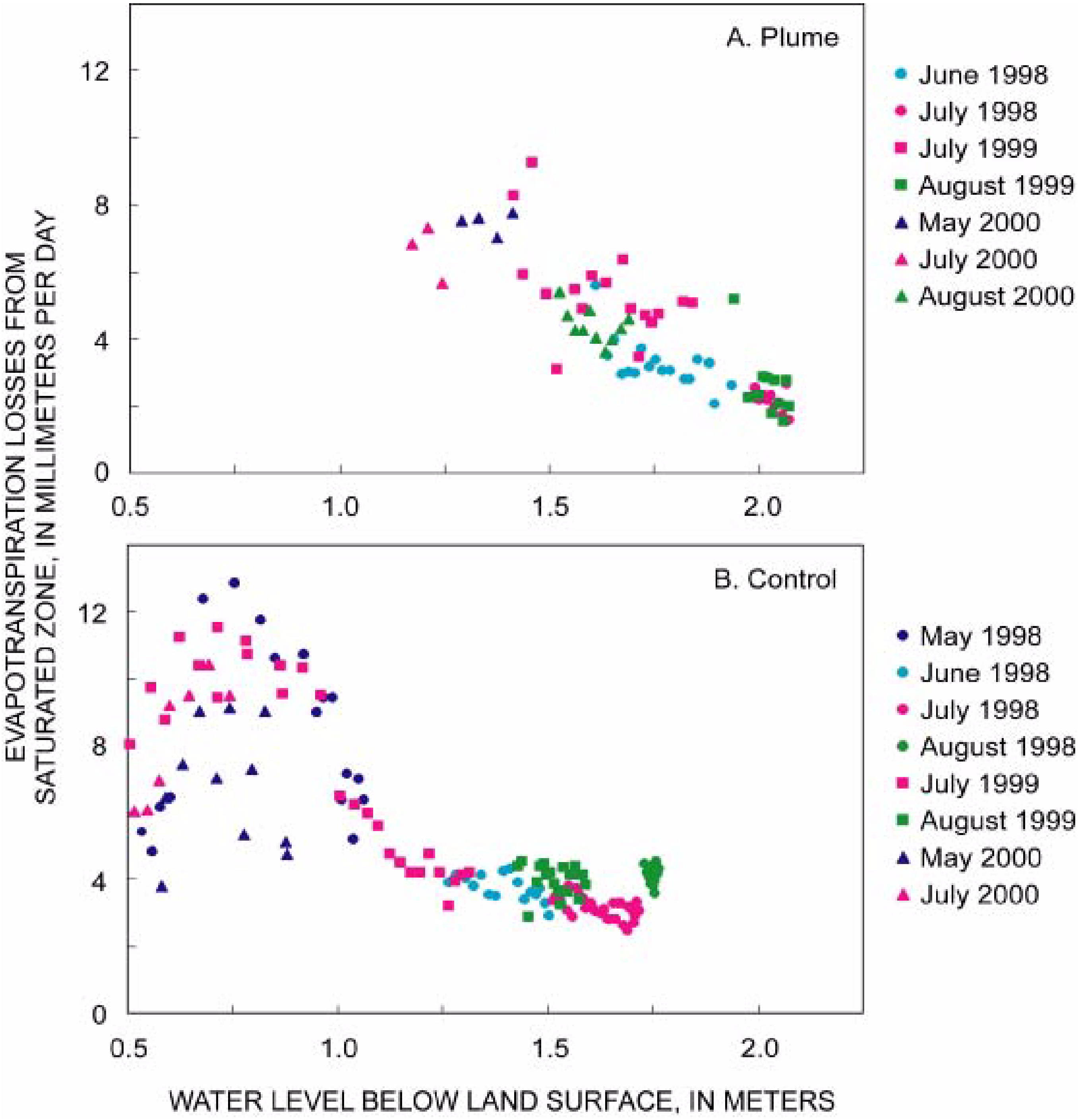


Figure 6. Evapotranspiration (ET) rates vary with depth of water table below land surface near the Plume (A) and Control (B) sites at the Norman Landfill, Norman, Oklahoma. Each data point is one day's ET rate, representing water loss from the saturated zone, determined by White's (1932) method on days during the growing season that had obvious diurnal water-table fluctuations.

rate, reflecting uncertainty in the S_y parameter, but the pattern of maximum ET when the water table was about 0.75 m below land surface was repeated during different months and years, suggesting that most roots are in that zone. Calculated pan evaporation from Central Oklahoma during the 2002-03 growing season averaged about 7 mm/day, with a maximum of 12 mm/day (Oklahoma Evapotranspiration Model, 2003); it was assumed that pan evaporation would be an upper limit for phreatophyte ET. The decrease in ET rate with increasing depth to water table probably reflects two effects: first, at higher water table, both evaporation and transpiration contribute to water losses from the saturated zone, whereas at lower water tables, losses are mostly due to transpiration; secondly, as the water table gets deeper, fewer plants have root systems that reach it.

Recharge Estimates Using Stable Isotopes of Water

The variation in stable isotopes in water at the site was used to identify the different sources of water. Figure 7 illustrates the distinct compositions of ground water with different sources in the three cluster wells, using δ^2H and δ^{18}O values from the April 2000 data set. Isotopic composition of water from different depth levels in the wells plots along mixing lines between leachate-contaminated ground water, slough water that is isotopically enriched due to evaporation, and infiltrated precipitation. The end members of landfill leachate and volume-weighted average precipitation are plotted for comparison. Instead of a slough water end member, the evaporation trend based on all the slough samples is shown, as many of the slough water values plot too far off scale to fit on the figure. The landfill leachate has distinctive deuterium enrichment, averaging 31 ‰, and as much as 45 ‰ more enriched than precipitation, probably due to methanogenesis (Hackley and others, 1996). This deuterium signature can be used to identify leachate in the wells. The water that has been in the slough during summer has undergone evaporation, so has a different isotopic signature than native ground water or leachate. Ground water at the deeper levels of the Control well that is enriched in oxygen-18 relative to the local meteoric water line (LMWL) is assumed to have a slough water component. The general origins of water at each sampling depth can be identified by these differing isotopic signatures, however, mixing processes and large outfluxes due to transpiration during the growing season complicate the interpretation of recharge rates from the data.

Precipitation has varying isotopic compositions, depending on the temperature, type, and history of the weather system that produces it. Seasonal variations in precipitation isotopes are most pronounced at higher latitudes. A predictable sinusoidal cycle of yearly variations is not present for the isotopic record at Norman, Oklahoma (latitude about 35°; fig. 8); the most depleted and enriched isotopic values are not confined to winter and summer periods, respectively. The seasonal isotopic signal was not optimal for tracing recharge, however, large precipitation events with distinct isotopic signatures may be used to provide information on timing of infiltration. Several such events occurred during the period of this study, but only two were useful for tracking recharge. The event that could be traced in all the wells occurred in the fall of 1998, at the end of the growing season. This was the only time that water stayed in the aquifer system long enough for its transport to be followed. By repeated sampling over time it was possible to track the vertical movement of water from this event in the aquifer.

Water types at the three sites (Plume, Slough Bank, and Control) were classified using isotopic composition, specific conductance, and chloride. The offset of a ground-water sample in either δ^2H or δ^{18}O from the local meteoric water line was used as a parameter along with a solute parameter (specific conductance or chloride) to distinguish recharge from underlying ground water. To determine the stable isotope offset parameter, the Local Meteoric Water Line (LMWL) [δ^2H = 7.5(δ^{18}O) + 11.7] was calculated using the biweekly rainfall record during the period of study. The amount of offset of either ^{2}H or ^{18}O from the LMWL was calculated for ground-water samples from each well level. For ^{2}H and ^{18}O, respectively:

$$^{2}Hoffset = |\delta^{18}Oa + b| - |\delta^{2}H|$$

$$^{18}Ooffset = |(\delta^{18}H - b)/a| - |\delta^{18}O|$$

where *a* is the slope of the local meteoric water line (7.5 for this site), and
b is the intercept (11.7 for this site).

The offsets from the LMWL were used rather than the isotopic values, because although precipitation and background ground-water composition varied, their isotopic composition was generally on the LMWL. Oxygen-18 in water from the slough was generally offset below the LMWL due to evaporation, and leachate deuterium was always offset above the LMWL due to methanogenic enrichment. Therefore, water mixed with leachate or slough water could be distinguished by the amount of offset from the LMWL, independent of the large variations in precipitation isotope values. The offset method was less sensitive when both water types were isotopically enriched; for example, in distinguishing slough water in a mixture of slough water and leachate, the calculated ^{18}O offset decreased with increasing ^{2}H-enrichment, but the method still worked to separate the water types.

For the Plume site, ^{2}H offset, specific conductance and chloride were used to distinguish infiltrated recharge from leachate (fig. 9A). For the Slough Bank site, ^{18}O offset and specific conductance were used to distinguish fresh water recharge (slough water and infiltration) from the underlying leachate (fig. 9B). For the Control site on the alluvial plain, specific conductance was similar in the two types of water, so ^{18}O offset and chloride were used to distinguish infiltrated recharge from the underlying ground water (fig. 9C). Nearly all the water in the Control well had an isotopic signature affected by evaporation (as shown by ^{18}O offset >0), but the water at deeper levels in the well was more offset and had relatively high chloride, and appeared to originate partly from the slough. The

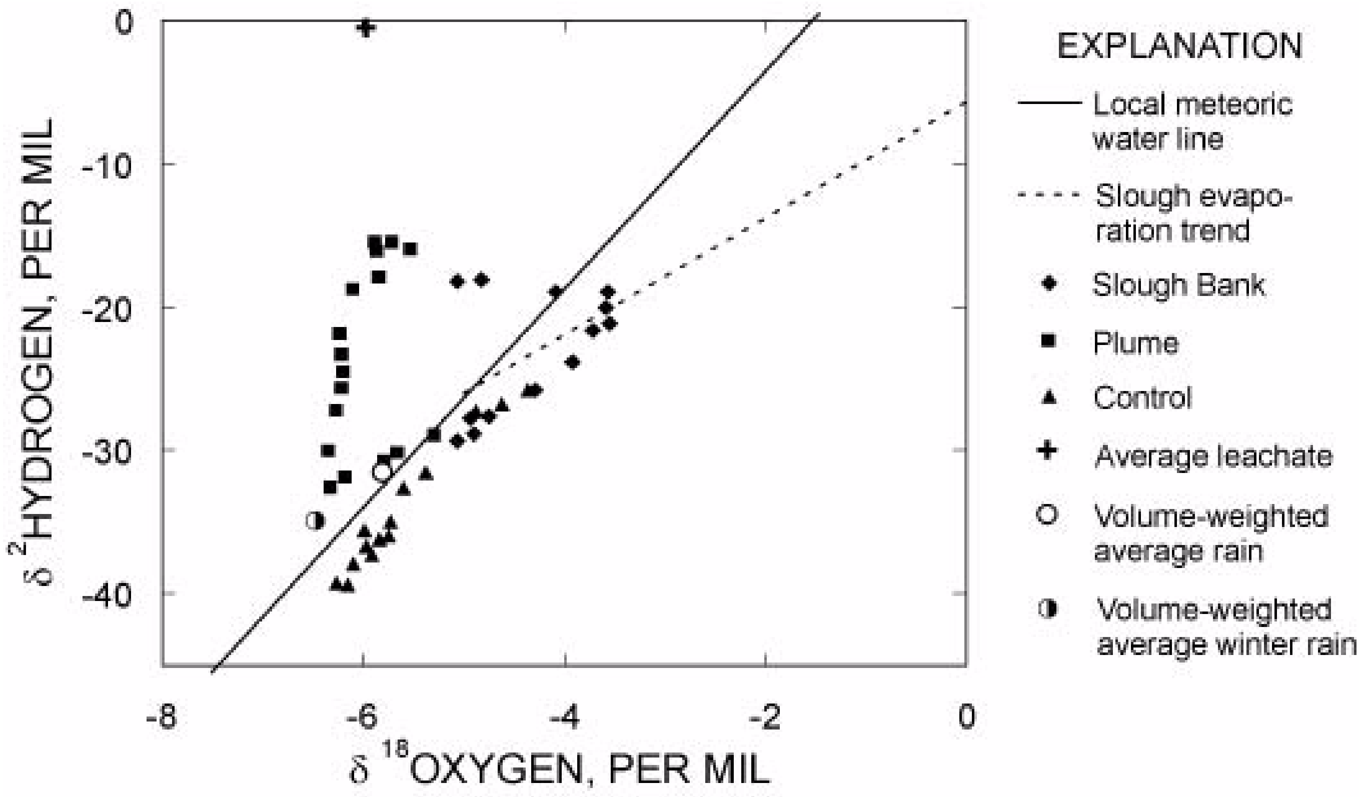


Figure 7. Isotopic composition of water samples from all depths of the cluster wells at Plume, Slough Bank and Control sites at the Norman Landfill, Norman, Oklahoma, from the April 2000 sampling. Local meteoric water line ($\delta^2H = 7.5\ \delta^{18}O + 11.7$), slough evaporation trend, volume weighted average precipitation and volume weighted average winter precipitation are shown for comparison. The slough evaporation trend is a regression line based on 29 samples; the values are not shown because most fall outside the scale of the plot.

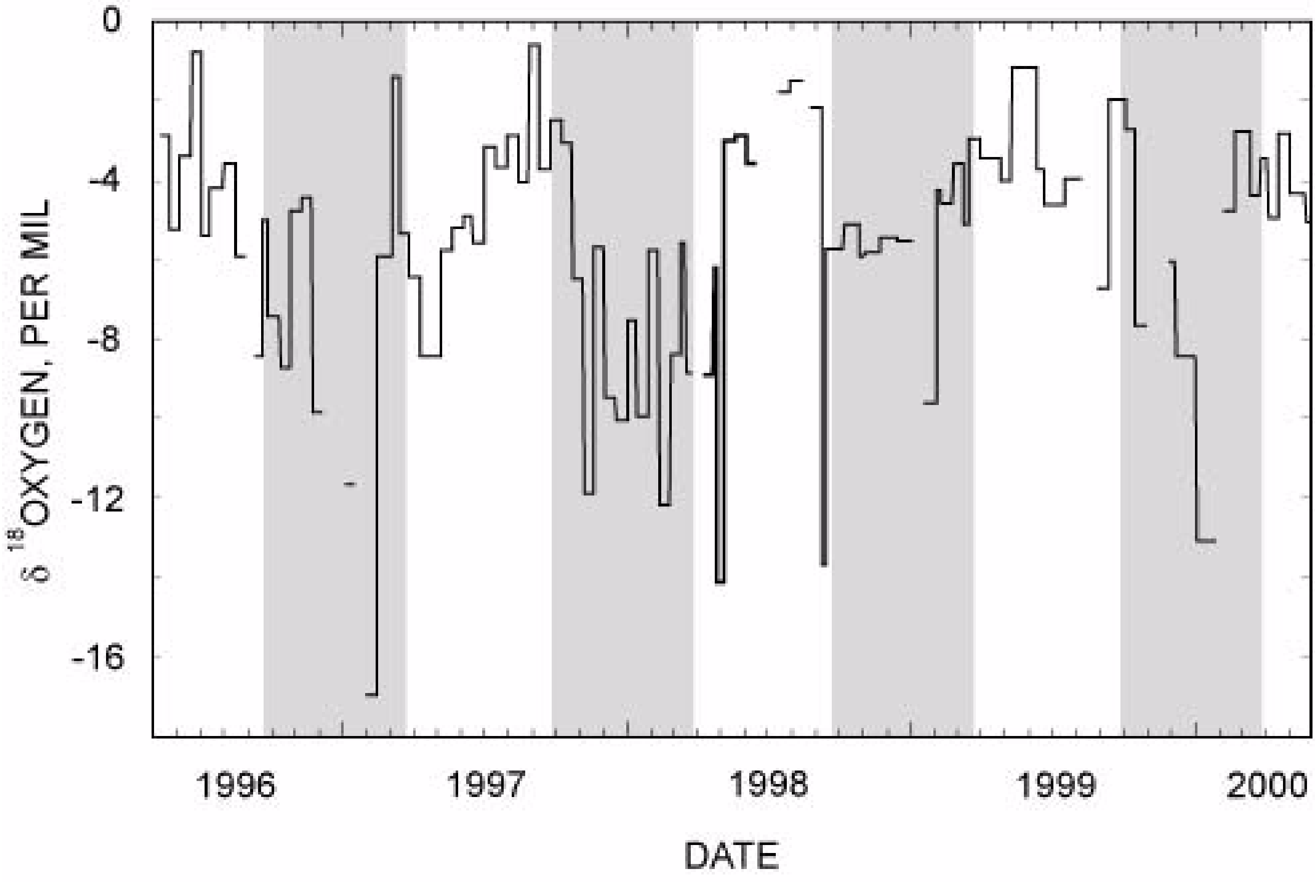


Figure 8. Oxygen-18 composition of rainfall at the Norman Landfill, Norman, Oklahoma, for biweekly samples taken May 1996 through May 2000. Horizontal segments of the line represent the bulk precipitation oxygen-18 value over the length of each sampling period, and gray shading denotes winter (September 21 to March 21). Breaks in the line denote periods without rainfall or missing data; data are listed in appendix 1.

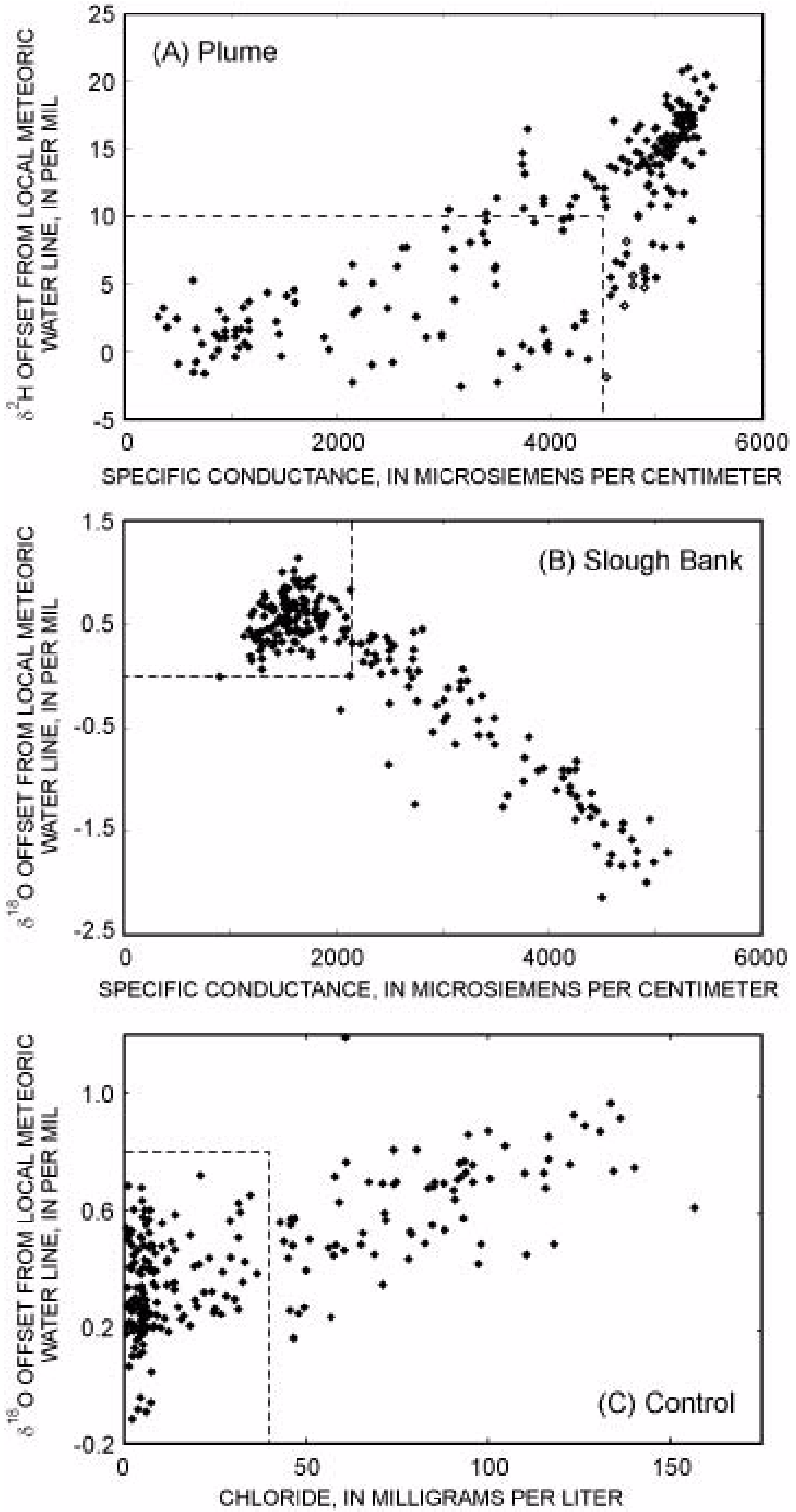


Figure 9. Scatter plots of chemical data from each sampling at each level of the cluster wells, showing mixing between recharge and underlying ground water at the Norman Landfill, Norman, Oklahoma. Dashed lines (-----) enclose the samples designated as recharge at each site. (A) Plume site, recharge determined using specific conductance and the offset of deuterium (δ^2H) from the local meteroric water line. Open symbols ◊ show additional samples designated as recharge on the basis of chloride. (B) Slough Bank site, recharge determined using specific conductance and the offset of oxygen-18 (δ^{18}O) from the local meteoric water line. (C) Control site, recharge determined using chloride and the offset of oxygen-18 (δ^{18}O) from the local meteoric water line.

background chloride level for ground water on the alluvial plain is about 26 milligrams per liter (mg/L) (Schlottman, 2000), whereas the deeper levels in the Control well averaged 92 mg/L. Slough water had median chloride concentration of 214 mg/L, with a range of 18-2,360 mg/L (the higher value at the lowest water volume). Criteria that were used to distinguish recharge water from underlying water in each well are listed in Table 2. The criteria also are marked as dividing lines on figs. 9A - 9C. The criteria are subjective; with the mixing between the two water types and variations in end-member composition there was no consistent demarcation between recharge and underlying water. In the Plume well, for example, the ^{2}H offset and specific conductance showed the best demarcation between water types, but high specific conductance was not uniquely associated with leachate. Incoming recharge added solutes from the unsaturated zone and from redox processes. The criteria for leachate, therefore, included chloride as well as ^{2}H offset and specific conductance.

Figures for each sampling period showing the profiles of δ^2H or δ^{18}O and either specific conductance or chloride for each depth interval in the well are given in appendix 2. Different coloring shows the classified water type defined by criteria in table 2, illustrating the layer of recharge water overlying the leachate plume or background ground water. After the water types were classified, a monthly estimate of recharge infiltrated through the unsaturated zone could be made at the Plume and Control sites. For the Slough Bank site, the amount of water in the shallow saturated zone originating from the slough could be quantified over time.

The recharge layer thickness was determined using the midpoint of the screen altitude; the uncertainty in the calculated thickness is ± 7.5 cm (half the screen length in the multilevel samplers). Change in recharge layer thickness was calculated for each sampling interval (generally monthly), with the month-to-month change in thickness taken to represent either net infiltration or net loss due to transpiration. The positive changes in thickness were multiplied by S_y to obtain millimeters of recharge to compare to rainfall amounts. For the Slough Bank site, possible components of the fresh water layer were slough water, infiltration through the local unsaturated zone, and upgradient ground water that flowed under the slough. The fraction of the fresh water layer that had originated in the slough was calculated using a simple two-component mixing model. The slough water was assumed to be offset in ^{18}O from the LMWL by the average amount for all samples (+2 ‰, with a range of 0 to +9.4 ‰), and the background ground water and infiltrated water were assumed to have no offset. The fraction of slough water was applied to the total thickness of the fresh water layer to obtain an estimate of slough recharge at the location of the well. This method may underestimate the recharge from the slough; underestimation is discussed further in the section “Recharge Estimates for the Slough Bank Well.”

Recharge Estimates From Rises in Water Table

Recharge was estimated from the rise in water levels at two time scales: for each rain event and the net rise between sampling periods. Water-level rises resulting from individual

Table 2. Criteria for distinguishing leachate or recharge water at the three study sites, Norman Landfill, Oklahoma.

[‰, per mil; <, less than; >, greater than; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; --, criterion not used.]

Water type and site	^{18}O offset	^{2}H offset		Chloride		Specific conductance
Leachate at Plume	--	> 10 ‰	OR	> 225	AND	> 4,500 µS/cm
Recharge at Slough Bank	> 0 ‰	--	AND	--		< 2,150 µS/cm
Recharge at Control	< 0.8 ‰	--	AND	< 40 mg/L		--

rain events (described in the section "Determination of Specific Yield") were summed over the period between sampling dates (Timlin and others, 2000; Rasmussen and Andreasen, 1959). The water-level rise was calculated from the rising portion of each ground-water hydrograph, without adding the amount of additional recharge estimated from continuing the recession curve until the peak of the rise. The rise generally occurred so quickly that this amount was negligible. Total water-level rise for the sampling period was multiplied by a S_y value of 0.11 to obtain millimeters of recharge for comparison to rainfall. The estimate based on individual rain events may have a higher degree of error at the Control site because of the effects of local surface water on ground-water fluctuations.

The longer time-scale estimate of recharge was based on the change in water level between sampling periods. The time between sampling was usually 4-5 weeks, although there were three shorter (9-12 day) sampling intervals to study large storm events in September and October 1998. The difference between water levels measured on consecutive sampling dates was calculated, and any increase in water level was multiplied by S_y of 0.23. This S_y value may lead to overestimation of recharge for periods shorter than about 30 days.

Comparison of Recharge Estimates Obtained by Chemical and Physical Methods

Recharge estimates based on chemical (infiltrated recharge layer thickness) and physical (event-based and monthly water-level rise) measurements are shown in figures 10A and 10B. The change in the recharge layer thickness or change in water level in millimeters of water are shown in bar graphs - positive values denote increasing layer thickness or water level, and negative values represent decreasing layer thickness or water-level decline. For monthly measurements, a S_y value of 0.23 was used to adjust field values to estimates of water gained or lost, and for estimates based on the sum of individual rain events, a S_y value of 0.11 was used.

Recharge patterns were similar over time at the Plume and Control sites, but at both sites, results from the three different methods of estimating recharge for each sampling period generally did not agree. Recharge estimates based on the sum of water-level rises after individual rain events, as expected, were larger than estimates from monthly measurements during the growing season, as water may recharge the aquifer but be removed shortly thereafter by transpiration. However, the sum of event-based rises was frequently larger than rainfall amounts at the Control site, an indication that water-level rise was not entirely due to infiltration at that site. Recharge from the layer thickness or monthly water-level rise methods exceeded rainfall in three instances: the period from mid-October to mid-November 1998 for both the Plume and Control sites, and the period from January 5 to February 3, 1999, for the Plume site. The recharge amount exceeding rainfall may have represented a transfer of previous rainfall from the unsaturated zone to the saturated zone, as the unsaturated zone has its largest storage capacity after a dry summer. Precipitation also may have been snow, or frozen at the surface, during the coldest part of winter so that infiltration would be delayed until melting occurred. The recharge layer, as defined by chemical criteria, disappeared at the Plume site from September to November 1999, while at the Control site, a layer of recharge water could be identified throughout the entire study period.

The overall recharge estimates shown in table 3 were calculated from the sum of recharge layer thickness increases and monthly water-level rises over the study period, excluding sampling intervals with declining water level or decreasing layer thickness. Recharge is reported as a percentage of the total rainfall over the measurement period (regardless of rising or declining water levels), using both the field and laboratory-determined S_y values.

For the Plume site, the recharge layer thickness method yielded an estimate for total recharge that was larger than that from monthly water table rises (46 percent and 34 percent of rainfall, respectively, for $S_y = 0.23$). As previously discussed, there was some uncertainty in setting criteria for fresh infiltration at this site -the degree of deuterium enrichment did not necessarily correlate with the specific conductance of a sample (fig. 9A). The conceptual model of the recharge process at the Plume site that was obtained from chemical and physical methods also was different. Rain fell and water levels rose from September to mid-November 1999, but isotopic signatures and solute chemistry indicated that there was effectively no infiltration reaching the water table (fig. 10A and appendix 2, figs. 2-14 and 2-15). This suggests that water-level increases occurred due to lateral flow of ground water rather than infiltration, as was seen at the Konza Prairie site in Kansas (Macpherson and Sophocleous, 2004). There is consistently higher head within the landfill mound that could cause a water-level rise without local infiltration reaching the water table.

At the Control site, despite the fact that monthly changes in recharge layer thickness and water level did not correlate each month, over the long term the total recharge estimate was nearly the same by both methods (34 percent and 36 percent of rainfall, respectively, for $S_y = 0.23$). Comparing the Plume and Control sites, the estimates of recharge were similar for the water-level method, 34 and 36 percent of rainfall, respectively, for $S_y = 0.23$; whereas the layer thickness method at the Plume site yielded larger recharge estimates than at the Control site (46 and 34 percent, respectively).

An overall recharge estimate also was done using the sum of water-level rise from rain events at the Plume site. This estimate was not done for the Control site because event-based recharge totals frequently exceeded rainfall for the sampling period, for unknown reasons. This value was 64 percent of rainfall; as expected, it was higher than the estimates from the methods that calculated recharge on a longer time scale because it included recharge during the growing season that may have a short residence time in the aquifer.

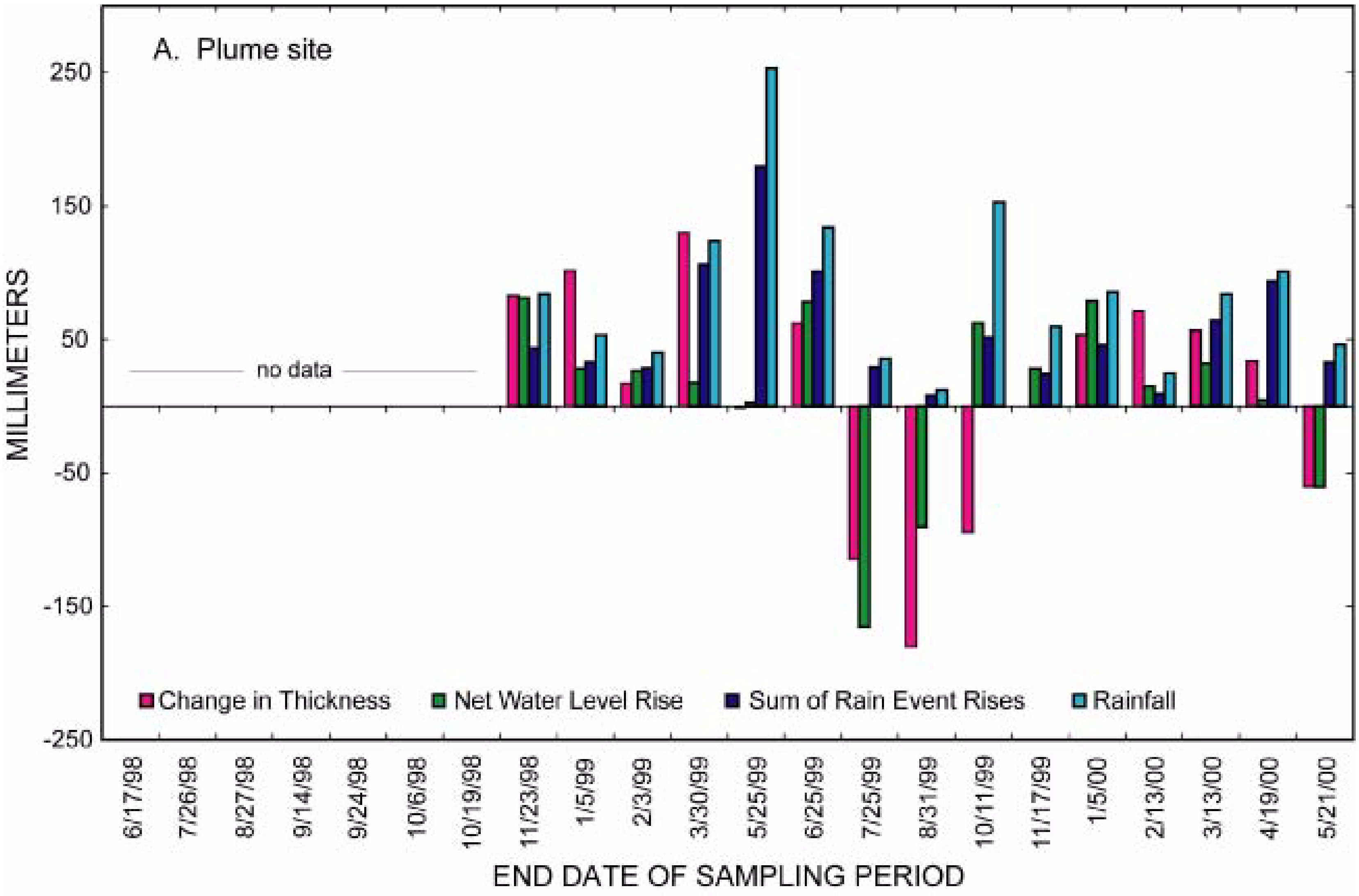


Figure 10A. Recharge estimated by three methods and compared to rainfall at the Plume (A) and Control (B) sites at the Norman Landfill, Norman, Oklahoma. The bars show millimeters of water added or removed from the saturated zone, as estimated by three methods: the change in thickness of the recharge layer as determined by isotopes and chemical constituents, the net water-level rise or fall during the sampling period determined by water-level monitors, and the sum of water-table rises after rain events during the sampling period. Rainfall was the total during the sampling period from the tipping-bucket gage at the weather station. A missing bar, if not otherwise explained, means that there was no change during the sampling period. A specific yield value of 0.23 was used for the layer thickness and net water-level rise recharge estimates, and a value of 0.11 was used for the event-based recharge estimates.

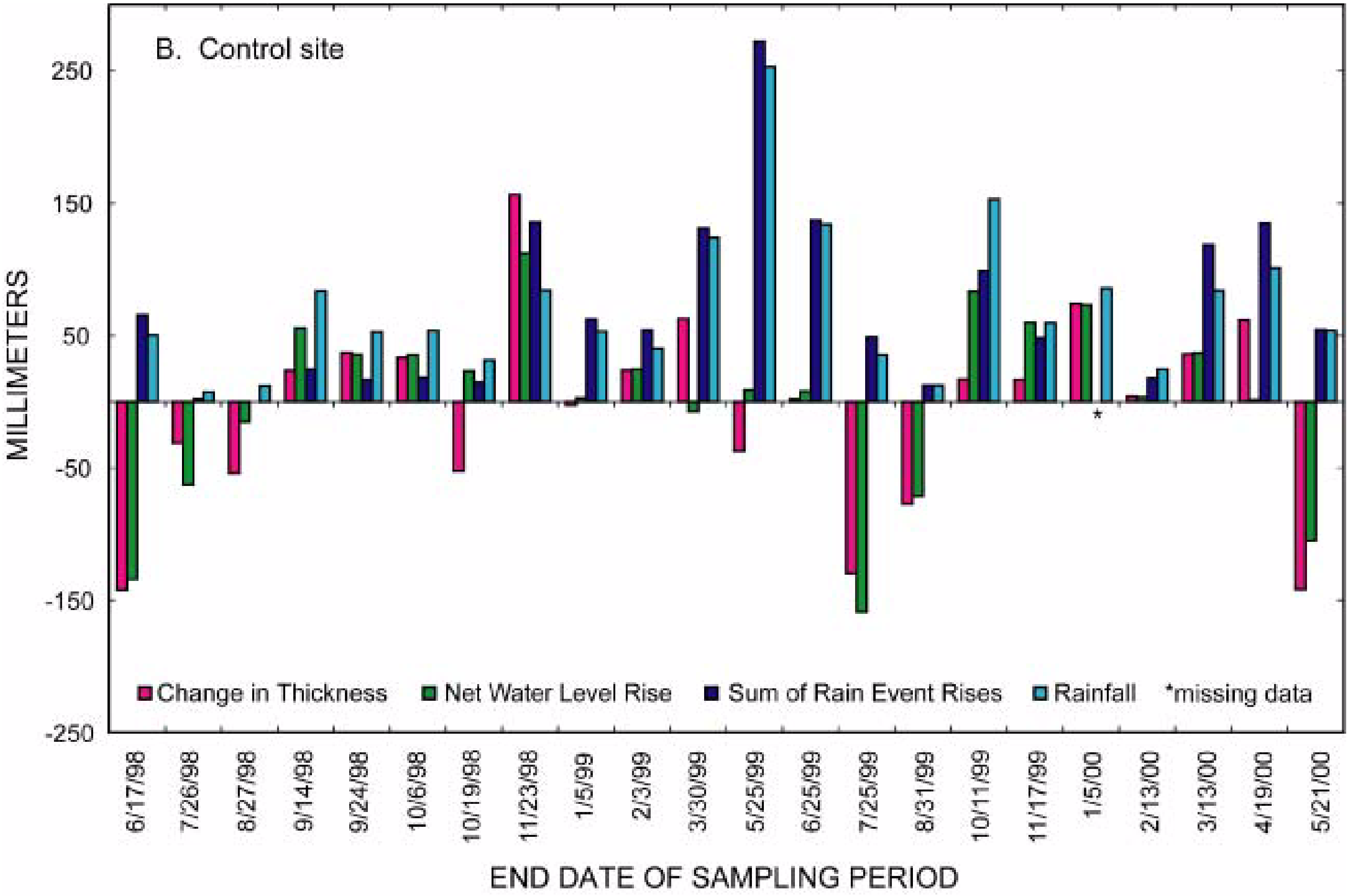


Figure 10B. Recharge estimated by three methods and compared to rainfall at the Plume (A) and Control (B) sites at the Norman Landfill, Norman, Oklahoma. The bars show millimeters of water added or removed from the saturated zone, as estimated by three methods: the change in thickness of the recharge layer as determined by isotopes and chemical constituents, the net water-level rise or fall during the sampling period determined by water-level monitors, and the sum of water-table rises after rain events during the sampling period. Rainfall was the total during the sampling period from the tipping-bucket gage at the weather station. A missing bar, if not otherwise explained, means that there was no change during the sampling period. A specific yield value of 0.23 was used for the layer thickness and net water-level rise recharge estimates, and a value of 0.11 was used for the event-based recharge estimates.

Table 3. Total recharge estimates for two sites at the Norman Landfill, Norman, Oklahoma, using three methods of determining recharge. Recharge was determined for the period May 1998 – May 2000 at the Control site and for October 1998 – May 2000 at the Plume site. Values are reported as the fraction of total rainfall (sum of sampling-period recharge times S_y, divided by rainfall), using the range of measured values for S_y.

[%, percent; mm, millimeters; S_y, specific yield; --, not determined].

	Layer thickness method – monthly net increases	Water-level method –monthly net rises	Water-level method – precipitation event rises
Plume Site – October 1998 to May 2000			
Sum of measured water-level rises or layer thickness increases, mm	2,626	1,981	7,741
[1]Rainfall, mm	1,322	1,322	1,322
Recharge as% of rainfall; $S_y = 0.11$	22	16	64
Recharge as % of rainfall; $S_y = 0.23$	46	34	--
Control Site – May 1998 to May 2000			
Sum of measured water-level rises or layer thickness increases, mm	2,294	2,454	--
[1]Rainfall, mm	1,589	1,589	--
Recharge as % of rainfall; $S_y = 0.11$	16	17	--
Recharge as % of rainfall; $S_y = 0.23$	34	36	--

[1] Rainfall amounts are the total for the time period noted, regardless of whether water levels were increasing or decreasing.

Recharge Estimates for the Slough Bank Well

The thickness of the fresh water layer overlying the leachate at the Slough Bank well was directly correlated with the water level in the slough at each monthly sampling, except when the slough was dry. This layer was assumed to be a mixture of three possible sources: water transported laterally from the slough, direct infiltration through the overlying sediments, and recharge from upgradient areas adjacent to the landfill.

The component of recharge from the slough was estimated by finding the average ^{18}O offset of the fresh water layer from the LMWL each month, then estimating the fraction of slough water on the basis of that offset, assuming a slough water ^{18}O offset of 1.9 ‰ (the average offset measured in samples taken from the slough). The isotopic analyses suggest that on average, 29 percent of the fresh water layer at the Slough Bank well originated in the slough, with a range of 7-49 percent. Recharge unaffected by evaporation also may enter the aquifer from the slough, but cannot be distinguished from other sources. Therefore, the estimate of slough recharge may be conservative. This estimate of recharge cannot be extrapolated beyond the immediate area of the Slough Bank well, as recharge from the slough to the aquifer may differ significantly along the length of the slough. Recharge estimated by this method also would decrease with increasing distance from the slough bank, because of dilution of the slough water by infiltration.

The changes in isotopic composition found in the slough were not found in the ground water; the ^{18}O offset from the LMWL varied between 0.14 and 0.95 ‰ in the ground water and showed no definite seasonal pattern, whereas the slough isotopic composition had offsets of 0 to 9.4 ‰, showing a clear seasonal pattern of no evaporative effects in winter to strong evaporative signature in summer (fig. 11). Seasonal isotopic fluctuations may not be distinguishable in the well samples because there is very little volume when the slough water has undergone the most evaporation, and the dilution factor is high when the slough refills and the water infiltrates. The 7-meter

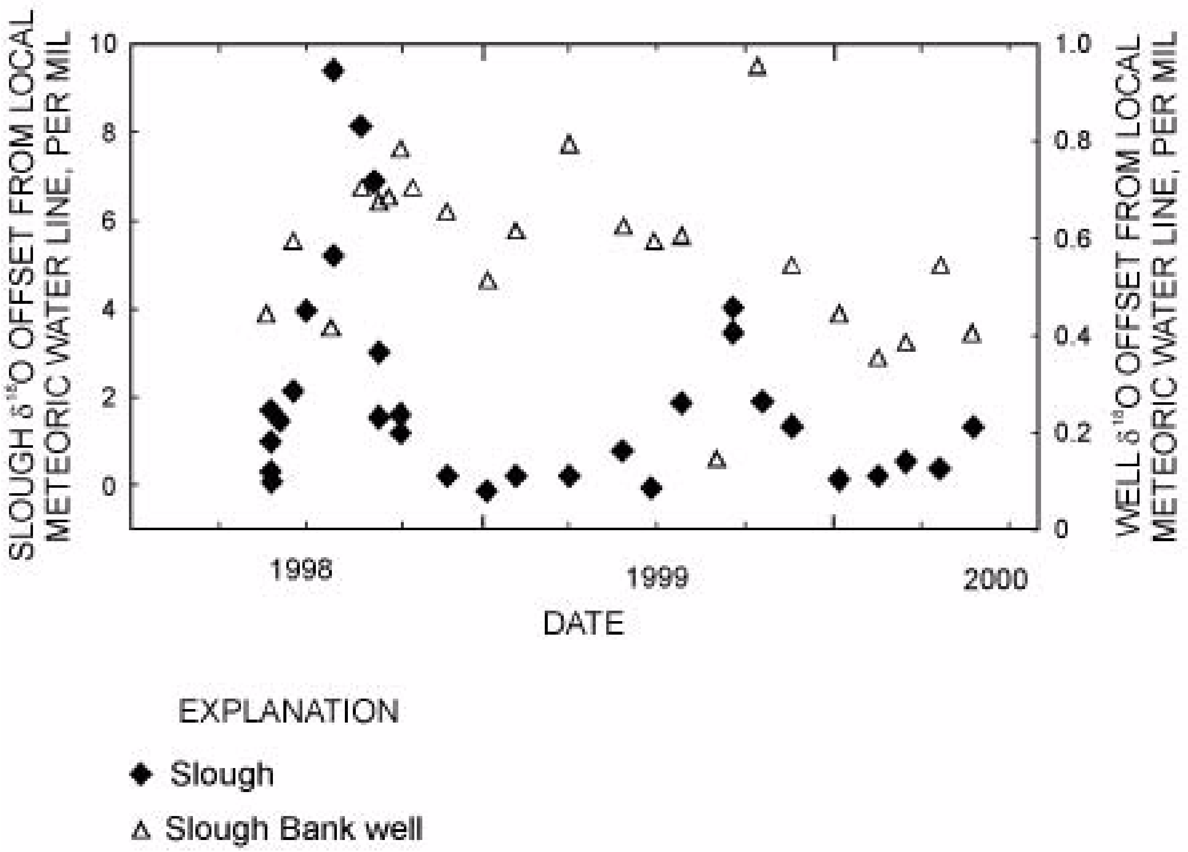


Figure 11. Amount of offset from the local meteoric water line found in slough water and in ground water from Slough Bank well at the Norman Landfill, Norman, Oklahoma. The values from the well are the average from all depths that were sampled. Note separate y-axis for the well samples.

distance between the slough and the well also would tend to smooth out variations in isotopic composition.

The data from the Slough Bank well give a good indication of the temporal variation in recharge from the slough. Estimates of slough water input to the aquifer over time correlated with the rainfall rate between sampling periods (fig. 12), with minimum input during both summers of the study and peaks in input after periods of high rainfall. This result suggests that most infiltration of the slough water is episodic, rather than occurring as a continuous process. As previously mentioned, the slough occupies the former river channel and the water is ponded because of a beaver dam, but there is some flow down the channel, through and around the dam, and out toward the Canadian River (fig. 1). Stage records show that rainfall events sharply raise the water level in the slough, probably a result of runoff from the channel upstream from the slough ponding at the beaver dam. The elevated water levels decline over hours to days. These events would push slough water into the aquifer for as long as the water level in the surface-water body was higher than in the surrounding aquifer. The correlation of infiltration rate from the isotopic method with the rainfall rate suggests an effective ground-water flow velocity of about 0.28 m/day. This velocity would result from an elevated water level in the slough of at least 0.1 m and a hydraulic conductivity of at least 7.0 x 10^{-5} m/s, as the well is about 7 meters from the slough. These values are reasonable for the site, although ground-water flow rates measured at another location at the site are on the order of 0.02 - 0.04 m/day (U.S. Geological Survey, unpub. data, November 18, 2003, through August 25, 2004). This observation implies fast transport of slough water during periods of infiltration.

Recharge Rate Estimates from Storm Events

Recharge rates were estimated by using a tracer (a rain event with significantly different isotopic composition) and measuring the rate of downward movement within the saturated zone. A rain event on September 13, 1998, could be traced as recharge in all the wells in the study. The rainfall total was 85 mm (3.35 inches) and the isotopic composition was $\delta^{18}O$ -13.7 ‰, $\delta^{2}H$ -99 ‰; a departure of 7.9 ‰ in $\delta^{18}O$ and 67 ‰ in $\delta^{2}H$ from the volume-weighted average rainfall at the site.

At the Plume site, the water from that storm reached the saturated zone of the aquifer some time between January 6 and February 4, 1999, with a deuterium signature of -48 ‰ (appen-

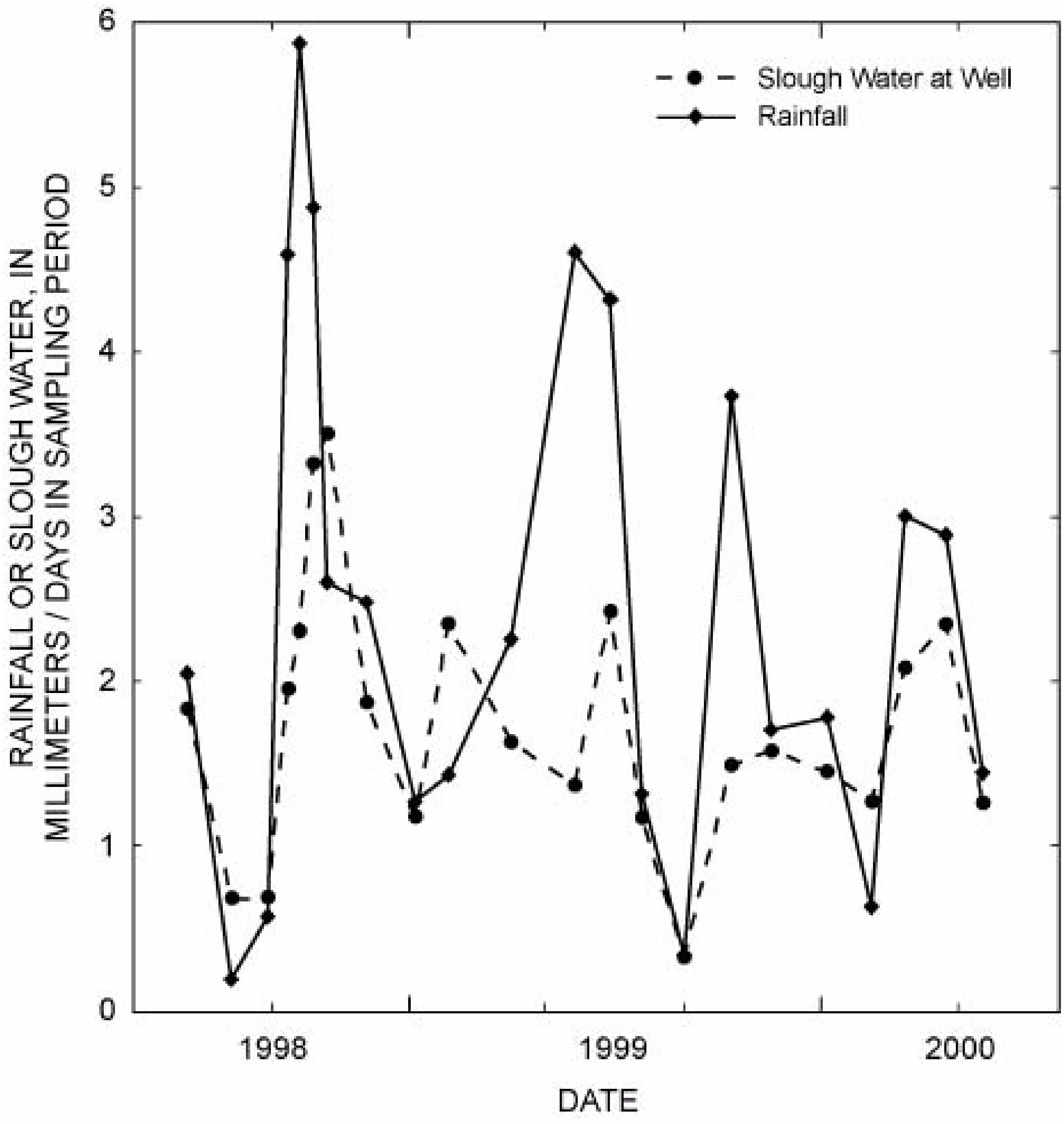


Figure 12. The fraction of slough water in the recharge layer at the Slough Bank well (Norman Landfill, Norman, Oklahoma) was correlated with rainfall. Slough water fraction of recharge layer thickness was multiplied by $S_y = 0.23$ to obtain millimeters of water. Total rainfall and slough water thickness values were calculated at the end of each sampling period, and were normalized by dividing each quantity by the number of days in the sampling period.

dix 2, fig. 2-8). The isotopic signature was more enriched than the original rain, due to mixing and evaporation processes during transport through the unsaturated zone, but still recognizable as rainfall from the September 13 storm as no subsequent rainfall had such a depleted isotopic signature. This water took approximately 4 months to move through the unsaturated zone. After it reached the saturated zone, subsequent samples showed the storm water moved downward in the aquifer until May 26, 1999; this movement represented a vertical velocity of about 9.8 mm/day. The water was at the same position June 24, 1999 (appendix 2, figs. 2-10 and 2-11); presumably the downward movement stopped because the growing season had advanced to the point that recharge was insignificant. The recharge rate at the Plume site for February 4-May 26 can be estimated as the vertical velocity times S_y, which would be 9.8 mm/day x 0.23, to yield 2.2 mm/day. This rate estimate requires the assumptions that recharge occurs as vertical flow and the rate of downward movement is constant with depth.

In the Control well, the September 13, 1998, storm event was seen in the saturated zone at the October 20, 1998, sampling, a transport time of 24 to 37 days in the unsaturated zone (appendix 2, fig. 2-5). This isotopically depleted water stayed effectively stationary, without moving downward in the aquifer, for months. Water accumulated above it in the next month, then the water level remained constant and there was no isotopic evidence of infiltration for the next 1 to 1.5 months, although there was 195 mm of precipitation during this period. Between February 2 and March 31, 1999, there was 124 mm of rainfall and the storm water moved down 740 mm. This movement yields a recharge rate of 13 mm/day x 0.23 = 3.0 mm/day. The behavior of the tracer storm water in the two wells suggests there was some inhibition of the infiltration process during the winter. Although the storm water infiltrated to the saturated zone sooner at the Control site, active downward transport within the saturated zone occurred during the same time period in both wells, with the apparent transport rate slightly higher at the Control site than the Plume site.

Water from another rain event on January 29-31, 1999, could be identified in the Control well, but the downward movement occurred during the growing season so the event could only be traced for two sampling periods (appendix 2, figs. 2-9, 2-10 and 2-11). The rain event measured 34 mm (1.33 inches) with isotopic composition of $\delta^{18}O$ -9.6 ‰, $\delta^{2}H$ -63 ‰. Water from this event appeared in the Control well by March 31, was at the same position May 26, then moved down 470 mm by June 28, a recharge rate of 3.3 mm/day, similar to the previous storm. The overlying water was then removed from the saturated zone by transpiration over the summer (appendix 2, figs. 2-12 and 2-13). This rain event was not seen in the saturated zone at the Plume well. During the winter of 1999-2000, there was only one rain event with distinctive isotopic composition and the rainfall amount was too small to be observed in the ground water.

The movement of the January 29, 1999, storm water in the ground water provides information about the recharge process at the Control site. Between March 31 and May 26, 1999, there was no apparent infiltration or vertical movement in the ground water. There was 253 mm (10 inches) of rainfall during this time, occurring in evenly spaced and evenly sized events of less than about 25 mm (1 inch) of rainfall. Between May 26 and June 28, 1999, there were more small, evenly spaced rain events, then a 5-day rain event totaling 112 mm (4.4 inches). This event seems to account for all the vertical movement that occurred in the ground water at that time. This observation suggests that recharge during the growing season occurs during large rain events; the vegetation utilizes all the water from any smaller rain events that occur. This observation also implies that recharge rates obtained in this way should not be extrapolated over time scales longer than the sampling interval.

At the Slough Bank well, the September 13, 1998, storm water was observed in the top screens of the well on February 4, 1999, a delay of nearly 5 months. The water moved down about 300 mm by June 28, but by July 26 it was gone, transpiration had removed it from the aquifer (appendix 2, figs. 2-8 through 2-11). Vertical transport was slower at this site than at the other two sites. A recharge rate was not calculated for this location, as flow may have been mostly horizontal, and transpiration began to have a large effect on the upper part of the saturated zone by late May, evidenced by the lack of further recharge above the storm water.

Recharge Rates and Seasonal Timing

For purposes of estimating input of fresh water and electron acceptors to the upper boundary of the contaminant plume, recharge rates and information on the seasonal timing of recharge are needed. Recharge rates estimated by several different methods are summarized in table 4. Although recharge amounts calculated by layer thickness and water level methods were often quite different for individual sampling periods, the average recharge rates for the entire study are similar for both the chemical and physical estimates, ranging from 1.3 to 1.6 mm/day. The rates calculated from vertical movement of storm water in the aquifer were higher, 2.2 to 3.3 mm/day, because these rates were calculated during shorter periods of active recharge.

The timing of recharge at the Plume and Control sites is shown in Figure 13 as recharge rates calculated for each sampling period from the layer thickness method. The layer thickness method of estimating recharge was the most reliable method for the study objectives, as the chemical evidence for infiltration of “new” water could be seen on a month-to-month basis. The recharge rates are in mm/day, obtained by dividing the increase in layer thickness by the time interval, and multiplying by $S_y = 0.23$ for each sampling period that there was recharge. Figure 13 covers the entire study period, however, the data set from the Plume site begins later, in November 1998. There was no recharge in July or August both years of the study, otherwise the rates and timing vary between sites and between years. Recharge rates were highest for the Control site in the fall of 1998. During the fall/winter of 1999-2000, recharge

Table 4. Recharge rates calculated by several methods for the Plume and Control sites, Norman Landfill, Oklahoma. Rates are in millimeters per day, using a S_y value of 0.23.

Site	Average recharge rate – layer method	Average recharge rate – water level increase method	Range of rates from individual sampling periods- both methods	Recharge rate, storm water tracers
Plume	1.6	1.3	0-4.9	2.2
Control	1.5	1.6	0-4.3	3.0 - 3.3

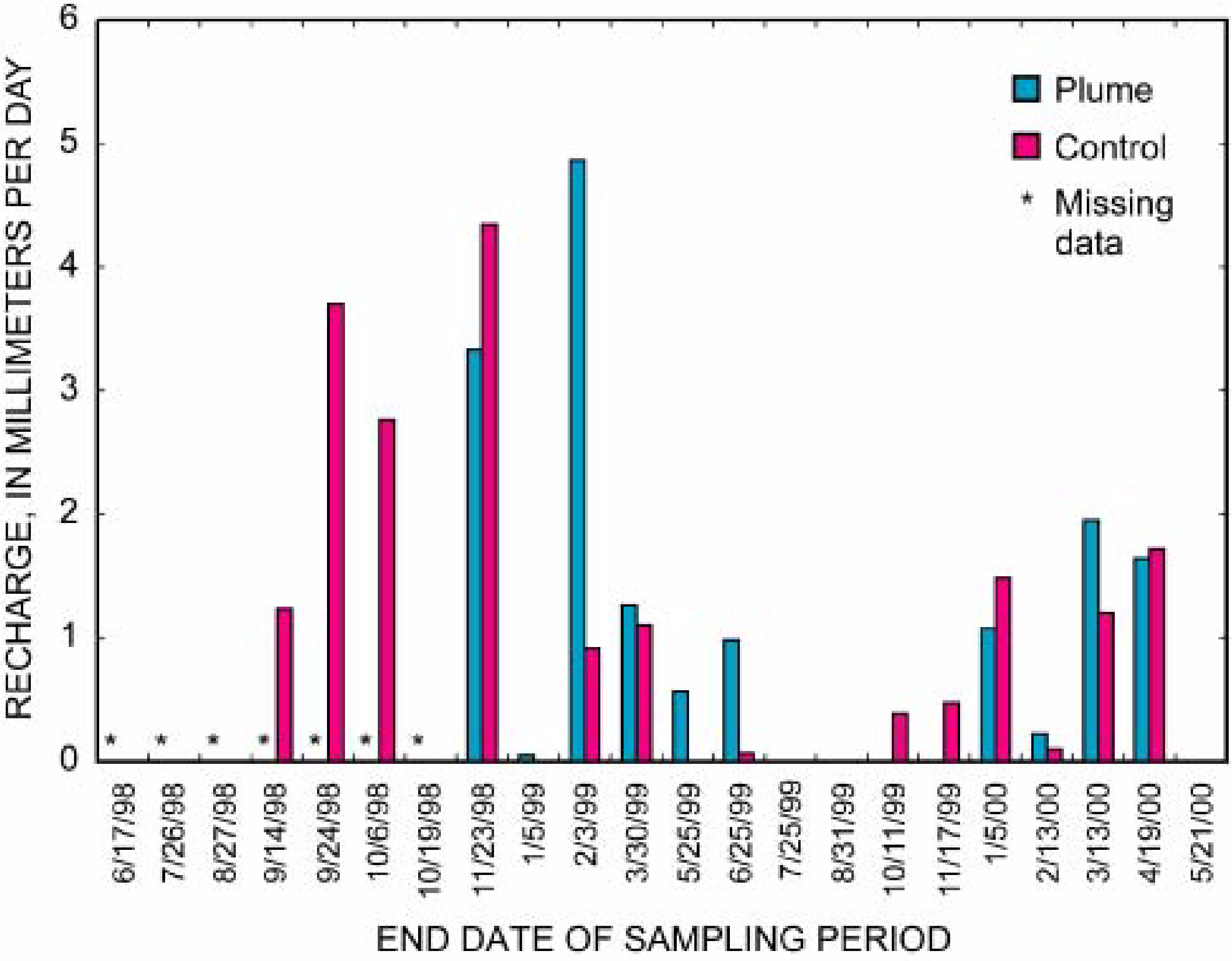


Figure 13. Temporal variation in recharge rates for the Plume and Control sites at the Norman, Landfill, Norman, Oklahoma. Rates shown are the increase in recharge layer thickness divided by the number of days in the sampling period. Sampling periods with no bar are either missing data for the Plume site or no recharge was measured for that sampling period.

rates were lower than in 1998, and most recharge occurred in the spring. During the period where there were data from both the Plume and Control sites, differences between the sites were present but were smaller than the differences between years.

The stable isotope composition of the alluvial plain ground water also provides indirect evidence of the timing of recharge to the area. The average background ground-water isotopic composition from an uncontaminated well upgradient from the landfill is -5.1 ‰ and -31 ‰ in $\delta^{18}O$ and $\delta^{2}H$, respectively, more similar to the volume-weighted average of all precipitation (-5.6 ‰, -30 ‰) than to volume-weighted average winter precipitation (-6.5 ‰, -35 ‰). This result suggests that large rain events during any season may contribute to recharge, not just late winter and spring rains as was found by Sophocleous and Perry (1985) in Kansas.

Summary

A leachate plume extends at least 225 meters downgradient from a closed municipal landfill in a shallow, unconfined alluvial aquifer. The landfill is located on the alluvial plain of the Canadian River in Norman, Oklahoma, and is one of the U.S. Geological Survey Toxic Substances Hydrology Program study sites. An investigation by the U.S. Geological Survey from May 1998 to May 2000 focused on quantifying the amount and timing of recharge to the alluvial aquifer from rainfall and from the slough near the landfill, to investigate how recharge may contribute to biodegradation processes in the leachate plume. The study was conducted at three sites near the landfill: 1) the Plume site, in the riparian zone between the landfill and the slough, 2) the Control site, on the alluvial plain downgradient from the slough, and 3) the Slough Bank site, in the riparian zone 7 meters downgradient from the slough.

Annual precipitation at the landfill is approximately 96 centimeters per year, and the growing season, when evapotranspiration affects ground-water levels, is from mid-April through October. Aquifer material is predominantly fine to medium grained sand with intermittent mud layers. The slough is a pond resulting from a beaver dam; this pond occupies a former channel of the Canadian River, about 50-100 meters downgradient from the edge of the landfill.

Precipitation for stable isotope analysis was collected biweekly, and precipitation amounts were measured with a tipping-bucket rain gage. Ground-water and surface-water levels were continuously monitored near the Plume and Control sites and in the slough. Shallow ground water was sampled approximately once per month in cluster wells with 15-centimeter screens spanning a 2-meter depth interval, and slough water samples were taken at the same times, with a bailer to obtain a depth-averaged sample of the water column. Stable isotopes, anions and specific conductance were measured in the ground-water and surface-water samples.

The recharge analyses, evapotranspiration analyses, and seasonal ground water observations for the Norman Landfill site, Norman, Oklahoma, indicate that the major factor determining the amount and timing of infiltration is evapotranspiration during the growing season. The water table is generally within 2 meters of the land surface, and the vegetation includes the phreatophyte species willow, cottonwood, and tamarisk, so that water losses occur directly from the saturated zone as well as from the unsaturated zone. Rain percolating through the unsaturated zone first has to satisfy evapotranspiration demand, which is significant during the growing season and may be insignificant in winter. Infiltration then fills the pores to the specific retention value of the sediment, which may require a relatively large amount of rainfall at the end of the growing season, when the water table is lowest. After this saturation is reached, additional infiltration water pushes previous infiltration toward the saturated zone. Water from smaller rain events may not reach the water table, especially during the growing season. Some rainfall may directly reach the saturated zone by way of macropores, but these are probably minor in this unconsolidated sand. Once water reaches the saturated zone, it may remain in the ground water for some period of time (fall/winter months) or be removed quickly by transpiration (spring/summer months).

Data from the Plume and Control sites indicated that ET rates decreased with increasing depth to the water table, and at the Control site, ET rates were at a maximum when the water table was about 0.75 meter below land surface. Transpiration by phreatophytes removed not only recent rainfall, but also water that had been in the saturated zone for some time. Isotopic profiles from both 1999 and 2000 showed that as the growing season proceeded, water was removed from the water table downward, with early summer and spring rain events removed first. At the Plume site, the chemically distinct layer of infiltrated recharge water was entirely removed from the aquifer by transpiration over the summer of 1999, while at the Control site, the layer of recharge water was present throughout the 2-year study.

Recharge from the slough to the aquifer was determined at one location about 7 meters from the bank of the slough. Isotopic evidence from this well suggested that on average, 29 percent of the fresh water layer was slough water, but this may be an underestimate because the source water in the slough did not always have an isotopic signature affected by evaporation during the winter. A strong correlation between monthly rainfall rates and the amount of slough recharge to the aquifer (based on the isotopic signature) indicates that much of the input of slough water to the aquifer is episodic, following rain events that temporarily raise the level of the surface water body above that of the aquifer. The fresh water layer at the Slough Bank site was always present over the 2-year study, even during the driest part of the summer.

The results of this study indicate that at this riparian zone site with its complex hydrology, multiple methods of estimating recharge yield a better understanding of the process than using a single approach. The contrasting stable isotope signatures of water at this site gave a detailed picture of recharge and transpiration processes that would not have been discernable from water-level or dissolved-solute measurements alone. Chemical and physical methods yielded similar estimates of overall recharge rates for the entire study period (1.3 to 1.6 millimeters per day), but recharge amounts obtained by each method for individual sampling periods were almost never the same, and in a few cases, even disagreed as to whether recharge was occurring. The methods that involved delineating the infiltration recharge layer and tracing of infiltration from individual storms provided direct evidence of infiltration reaching the saturated zone, but the amounts of recharge did not correlate well with rainfall during the measurement periods. Uncertainties in this approach arise from seasonal differences in the thickness of the unsaturated zone, leading to differences in the transport time of rainfall to the saturated zone, and variations in chemical composition and mixing within the saturated zone that tend to blur boundaries between different sources of water. Measurements of water-level fluctuations on event and monthly time scales were easy to obtain, but there was evidence that fluctuations in the water table were not entirely due to infiltration. Uncertainties in these recharge estimates arise from the effects of lateral flow and redistribution of water from areas with different water levels, for instance from the elevated water table under the landfill mound or from the surface water bodies in the area. For all methods of estimating recharge, the possible spatial and temporal variations in the S_y value are a source of uncertainty.

The data collected in this study show a distinct seasonality for the input of fresh electron acceptors to drive biodegradation processes in this contaminated ground water system. During the growing season, there is little or no recharge and a net loss of previously recharged water from the shallow alluvial aquifer. Most recharge occurs in the fall, winter, and spring, with relatively large rain events delivering the bulk of the recharge to the saturated zone of the aquifer from the unsaturated zone and from the slough. Therefore, biodegradation rates for contaminants in the upper fringes of the leachate plume may be correlated with recharge rates.

References

Bohlke, J.K., Smith, R.L., Coplen, T.B., Busenberg, E., and LeBlanc, D.R., 1999, Recharge conditions and flow velocities of contaminated and uncontaminated ground waters at Cape Cod, Massachusetts: Evaluation of δ^2H, δ^{18}O, and dissolved gases: *in* Morganwalp, D.W. and Buxton, H.T., eds., Toxic Substances Hydrology Program, Proceedings of the Technical Meeting, Charleston, S.C., 1999, U.S. Geological Survey Water-Resources Investigations Report 99-4018C, p. 337-347.

Christenson, S.C. and Cozzarelli, I.M., 2003, The Norman Landfill environmental research site: What happens to the waste in landfills?: U.S. Geological Survey Fact Sheet FS-040-03, 4 p.

Christenson, S.C., Scholl, M.A., Schlottmann, J.L., and Becker, C.J., 1999, Ground-water and surface-water hydrology of the Norman Landfill Research site: *in* Morganwalp, D.W. and Buxton, H.T., eds., Toxic Substances Hydrology Program, Proceedings of the Technical Meeting, Charleston, S.C., 1999, U.S. Geological Survey Water-Resources Investigations Report 99-4018C, p. 501-507.

Cozzarelli, I.M., Suflita, J.M., Ulrich, G.A., Harris, S.H., Scholl, M.A., Schlottmann, J.L., and Christenson, Scott, 2000, Geochemical and microbiological methods for evaluating anaerobic processes in an aquifer contaminated by landfill leachate: Environmental Science & Technology, v. 34, no. 18, p. 4025-4033.

Duke, H.R., 1972, Capillary properties of soils - influence upon specific yield: Transactions of the ASAE, v. 15, no. 4, p. 688-691.

Gerhart, J.M., 1986, Ground-water recharge and its effects on nitrate concentration beneath a manured field site in Pennsylvania: Ground Water, v. 24, no. 4, p. 483-489.

Gossard, C.M., Hornecker, M.M., and Kolar, R.L., 1998, Evapotranspiration Estimates for the Closed Norman, Oklahoma Landfill: *in* Morel-Seytoux, H.J., ed., Proceedings of the American Geophysical Union 18th Annual Hydrology Days, p. 111-120.

Guglielmi, Yves and Mudry, Jacques, 1996, Estimation of spatial and temporal variability of recharge fluxes to an alluvial aquifer in a foreland area by water chemistry and isotopes: Ground Water, v. 34, no. 6, p. 1017-1023.

Hackley, K.C., Liu, C.L., and Coleman, D.D., 1996, Environmental isotope characteristics of landfill leachates and gases: Ground Water, v. 34, no. 5, p. 827-836.

Healy, R.W. and Cook, P.G., 2002, Using groundwater levels to estimate recharge: Hydrogeology Journal, v. 10, no. 1, p. 91-109.

Klute, Arnold, ed., 1986, Methods of soil analysis. Part 1. Physical and Mineralogical methods: Agronomy series no. 9, 2nd edition, American Society of Agronomy, Madison, WI, 1180 p.

Lott, R. B. and Hunt, R.J., 2001, Estimating evapotranspiration in natural and constructed wetlands: Wetlands, v. 21, no. 4, p. 614-627.

Macpherson, G. L. and Sophocleous, M., 2004, Fast groundwater mixing and basal recharge in an unconfined, alluvial aquifer, Konza LTER Site, Northeastern Kansas: Journal of Hydrology, v. 286, no. 1, p. 271-299.

Marston, R.A., Paxton, S.T., Collins, K.L., and Pickup, B.E., 2001, Geomorphology and sedimentology of the Canadian River alluvium adjacent to the Norman Landfill, Norman, Oklahoma: report, Environmental Institute/Oklahoma Water Resources Research Institute, 74 p.

McGuire, K.J, DeWalle, D.R., and Gburek, W.J., 2002, Evaluation of mean residence time in subsurface waters using oxygen-18 fluctuations during drought conditions in the mid-Appalachians: Journal of Hydrology, v. 261, p. 132-149.

Meyboom, P., 1967, Ground water in the Assiniboine River drainage basin - Part II: Hydrologic characteristics of phreatophytic vegetation in south-central Saskatchewan: Geological Survey of Canada, Bulletin no. 139, 64 p.

Nachabe, M.H., 2002, Analytical expressions for transient specific yield and shallow water table drainage: Water Resources Research, v. 38, no. 10, p. 11-1 - 11-7.

National Oceanic and Atmospheric Administration, National Weather Service, 2003, Climate Information, accessed August 2003 at http://www.srh.noaa.gov/oun/climate/

Oklahoma Evapotranspiration Model, 2003, accessed August 2003 at http://agweather.mesonet.ou.edu/models/evapotranspiration/description.html

Rasmussen, W.C. and Andreasen, G.E., 1959, Hydrologic budget of the Beaverdam Creek basin, Maryland: U.S. Geological Survey Water-Supply Paper 1472, 106 p.

Rosenberry D.O. and Winter, T.C., 1997, Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlands in North Dakota: Journal of Hydrology, v. 191, p. 266-289.

Schaeffer, S.M., Williams, D.G., and Goodrich, D.C., 2000, Transpiration of cottonwood/willow forest estimated from sap flux: Agricultural and Forest Meteorology, v. 105, p. 257-270.

Schlottmann, J.L., 2001, Water chemistry near the closed Norman Landfill, Cleveland County, Oklahoma, 1995: U.S. Geological Survey Water-Resources Investigations Report 00-4238, 44 p.

Scholl, M.A. and Christenson, S.C., 1998, Spatial variation in hydraulic conductivity determined by slug tests in the Canadian River alluvium near the Norman Landfill, Norman, Oklahoma: U.S. Geological Survey Water-Resources Investigations Report 97-4292, 28 p.

Snyder, K.A. and Williams, D.G., 2000, Water sources used by riparian trees varies among stream types on the San Pedro River, Arizona: Agricultural and Forest Meteorology, v. 105, p. 227-240.

Sophocleous, Marios and Perry, C.A., 1985, Experimental studies in natural groundwater recharge dynamics: the analysis of observed recharge events: Journal of Hydrology, v. 81, no. 3/4, p. 297-332.

Sophocleous, Marios, 1985, The role of specific yield in ground-water recharge estimations: a numerical study: Ground Water, v. 23, no. 1, p. 52-58.

Stewart, M.K. and McDonnell, J.J., 1991, Modeling base flow soil water residence times from deuterium concentrations: Water Resources Research, v. 27, no. 10, p. 2681-2693.

Timlin, D.J., Starr, J.L., Cady, R.E., and Nicholson, T.J., 2000, Comparison of estimated ground-water recharge using different temporal scales of field data: U.S. Nuclear Regulatory Commission Report NUREG/CR-6653, Washington, DC, April 2000, 65 p.

Turner, J.V. and Barnes, C.J., 1998, Modeling of isotope and hydrogeochemical response in catchment hydrology: *in* Kendall, Carol and McDonnell, J.J., eds., Isotope Tracers in Catchment Hydrology, Elsevier Science, Amsterdam, p. 723-760.

Ulrich, G.A., Breit, G.N., Cozzarelli, I.M., and Suflita, J.M., 2003, Sources of sulfate supporting anaerobic metabolism in a contaminated aquifer: Environmental Science & Technology, v. 37, no. 6, p. 1093-1099.

Vitvar, Tomas and Balderer, Werner, 1997, Estimation of mean water residence times and runoff generation by ^{18}O measurements in a Pre-Alpine catchment (Rietholzbach, Eastern Switzerland): Applied Geochemistry, v. 12, no. 6, p. 787-796.

Weeks, E.P., 2002, The Lisse effect revisited: Ground Water, v. 40, no. 6, p. 652-656.

White, W.N., 1932, A method of estimating groundwater supplies based on discharge by plants and evaporation from soil - results of investigations in Escalante Valley, Utah: U.S. Geological Survey Water-Supply Paper 659, p. 1-105, 10 plates.

Appendixes

Appendix 1. Stable isotope values for biweekly rainfall at the Norman Landfill, Norman, Oklahoma, from May 1996 through May 2000.

[mL, milliliters; ^{2}H, deuterium; ^{18}O, oxygen-18; ‰, per mil; --, no data].

Sample	Volume (mL)	Delta ^{2}H (‰)	Delta ^{18}O (‰)	Start date	End date	Comment
NLFP-1	91	-13.7	-2.90	5/10/96	5/22/96	
NLFP-2	1,400	-31.3	-5.26	5/22/96	6/3/96	
NLFP-3	900	-15.3	-3.39	6/3/96	6/19/96	
NLFP-4	149	-2.2	-0.82	6/19/96	7/3/96	
NLFP-5	890	-30.3	-5.42	7/3/96	7/12/96	
NLFP-6	1,670	-20.9	-4.22	7/12/96	7/31/96	
NLFP-7	2,340	-13.5	-3.59	7/31/96	8/15/96	
[1]NLFP-8	450	-7.7	-1.38	8/15/96	8/15/96	Control, initial
NLFP-9	498	-36.7	-5.92	8/15/96	8/29/96	
[1]NLFP-10	450	-9.3	-1.33	8/15/96	8/29/96	Control, final
NLFP-11	0	--	--	8/29/96	9/10/96	
NLFP-12	570	-54.6	-8.43	9/10/96	9/18/96	
NLFP-13	950	-25.9	-5.03	9/18/96	9/25/96	
NLFP-14	900	-45.9	-7.44	9/25/96	10/11/96	
NLFP-15	250	-52.2	-8.74	10/11/96	10/25/96	
NLFP-16	2,000	-21.4	-4.77	10/25/96	11/8/96	
NLFP-17	303	-17.4	-4.46	11/8/96	11/22/96	
NLFP-18	530	-59.9	-9.87	11/22/96	12/5/96	
NLFP-19	0	--	--	12/5/96	12/20/96	
NLFP-20	0	--	--	12/20/96	1/3/97	
NLFP-21	74	-76.9	-11.7	1/3/97	1/16/97	
NLFP-22	0	--	--	1/16/97	1/30/97	
NLFP-23	310	-122.0	-17.0	1/30/97	2/14/97	
NLFP-24	900	-34.8	-5.94	2/14/97	3/5/97	
NLFP-25	59	6.4	-1.44	3/5/97	3/13/97	
NLFP-26	410	-27.3	-5.34	3/13/97	3/27/97	
NLFP-27	1,200	-35.7	-6.46	3/27/97	4/10/97	
NLFP-28	1,002	-55.5	-8.43	4/10/97	4/23/97	
NLFP-29	1,595	-54.4	-8.44	4/23/97	5/7/97	
NLFP-30	1,384	-33.8	-5.76	5/7/97	5/22/97	
[1]NLFP-31	1,220	-32.8	-5.21	5/22/97	6/5/97	Duplicate
NLFP-32	1,220	-31.2	-5.21	5/22/97	6/5/97	
[1,2]NLFP-33	2,500	-26.1	-4.91	6/5/97	6/16/97	Duplicate
[2]NLFP-34	2,500	-25.8	-4.95	6/5/97	6/16/97	
[1]NLFP-35	435	-33.4	-5.55	6/16/97	7/2/97	Duplicate
NLFP-36	435	-33.2	-5.59	6/16/97	7/2/97	
NLFP-37	150	-14.9	-3.17	7/2/97	7/17/97	
NLFP-38	288	-16.4	-3.69	7/17/97	7/31/97	
NLFP-39	1,469	-9.2	-2.90	7/31/97	8/14/97	

Appendix 1. Stable isotope values for biweekly rainfall at the Norman Landfill, Norman, Oklahoma, from May 1996 through May 2000. —Continued

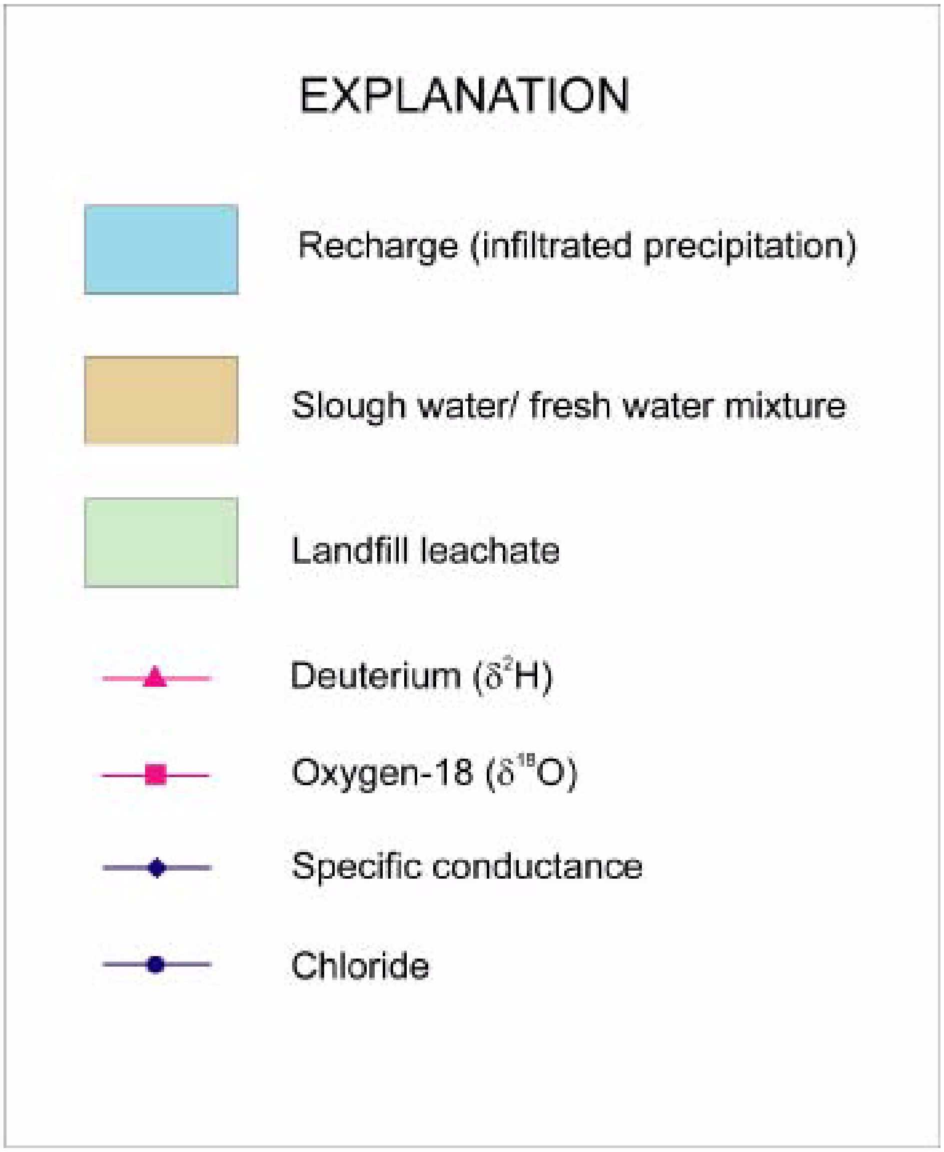
Sample	Volume (mL)	Delta ^{2}H (‰)	Delta ^{18}O (‰)	Start date	End date	Comment
NLFP-40	1,380	-19.8	-4.06	8/14/97	8/28/97	
NLFP-41	50	5.1	-0.61	8/28/97	9/11/97	
NLFP-42	1,861	-17.6	-3.74	9/11/97	9/25/97	
NLFP-43	216	0.3	-2.52	9/25/97	10/9/97	
NLFP-44	1,580	-8.6	-3.06	10/9/97	10/23/97	
NLFP-45	372	-31.8	-6.51	10/23/97	11/6/97	
NLFP-46	892	-73.8	-11.9	11/6/97	11/20/97	
NLFP-47	1,240	-26.4	-5.66	11/20/97	12/3/97	
NLFP-48	290	-51.5	-9.48	12/3/97	12/18/97	
NLFP-49	2,150	-61.8	-10.1	12/18/97	1/2/98	
NLFP-50	2,225	-43.2	-7.53	1/2/98	1/13/98	
NLFP-51	164	-61.4	-9.94	1/13/98	1/29/98	
NLFP-52	791	-25.7	-5.80	1/29/98	2/12/98	
NLFP-53	360	-83.5	-12.2	2/12/98	2/26/98	
NLFP-54	1,034	-54.8	-8.39	2/26/98	3/12/98	
NLFP-55	2,338	-23.6	-5.60	3/12/98	3/17/98	
NLFP-56	461	34.0	-8.86	3/17/98	3/26/98	
[1]NLFP-57	250	9.5	-0.39	3/26/98	4/9/98	Evaporated
NLFP-58	238	-56.1	-8.93	4/9/98	4/23/98	
NLFP-59	1,647	-30.5	-6.18	4/23/98	4/27/98	
NLFP-60	44	-105	-14.1	4/27/98	5/7/98	
NLFP-61	1,330	-8.8	-3.01	5/7/98	5/21/98	
NLFP-62	592	-10.5	-2.89	5/21/98	6/4/98	
NLFP-63	735	-20.9	-3.60	6/4/98	6/18/98	
NLFP-64	0	--	--	6/18/98	7/2/98	
NLFP-65	0	--	--	7/2/98	7/16/98	
NLFP-66	175	-8.92	-1.78	7/16/98	7/30/98	
NLFP-67	215	-7.31	-1.50	7/30/98	8/17/98	
NLFP-68	0	--	--	8/17/98	8/27/98	
NLFP-69	195	-12.0	-2.19	8/27/98	9/10/98	
NLFP-70	1,870	-98.6	-13.7	9/10/98	9/15/98	
NLFP-71	1,265	-34.8	-5.73	9/15/98	9/25/98	
NLFP-72	1,195	-31.4	-5.72	9/25/98	10/7/98	
NLFP-73	815	-30.3	-5.09	10/7/98	10/28/98	
NLFP-74	1,488	-28.4	-5.94	10/28/98	11/3/98	
NLFP-75	324	-24.8	-5.84	11/3/98	11/24/98	
NLFP-76	1,078	-27.7	-5.44	11/24/98	12/16/98	
NLFP-77	212	-21.4	-5.53	12/16/98	1/5/99	
NLFP-78	0	--	--	1/5/99	1/20/99	
NLFP-79	1,104	-62.7	-9.64	1/20/99	2/4/99	

Appendix 1. Stable isotope values for biweekly rainfall at the Norman Landfill, Norman, Oklahoma, from May 1996 through May 2000.—Continued

Sample	Volume (mL)	Delta ^{2}H (‰)	Delta ^{18}O (‰)	Start date	End date	Comment
NLFP-80	112	-21.3	-4.25	2/4/99	2/10/99	
NLFP-81	679	-20.3	-4.61	2/10/99	2/25/99	
NLFP-82	670	-9.9	-3.61	2/25/99	3/11/99	
NLFP-83	1,240	-24.1	-5.10	3/11/99	3/18/99	
NLFP-84	363	-11.9	-2.99	3/18/99	4/1/99	
[2]NLFP-85	2,370	-13.3	-3.44	4/1/99	4/28/99	
NLFP-86	1,035	-22.0	-4.02	4/28/99	5/12/99	
[2]NLFP-87	1,387	-3.2	-1.20	5/12/99	6/14/99	
NLFP-88	1,738	-15.0	-3.74	6/14/99	6/23/99	
NLFP-89	735	-25.7	-4.66	6/23/99	7/19/99	
NLFP-90	441	-13.0	-3.98	7/19/99	8/10/99	
NLFP-91	0	--	--	8/10/99	8/30/99	
NLFP-92	2,377	-38.5	-6.73	8/30/99	9/14/99	
NLFP-93	375	-4.4	-1.98	9/14/99	10/5/99	
NLFP-94	67	-14.7	-2.75	10/5/99	10/18/99	
NLFP-95	1,165	-39.3	-7.69	10/18/99	11/2/99	
NLFP-96	0	--	--	11/2/99	12/2/99	
NLFP-97	1,375	-28.5	-6.07	12/2/99	12/9/99	
NLFP-98	413	-49.3	-8.45	12/9/99	1/5/00	
NLFP-99	511	-91.9	-13.1	1/5/00	1/31/00	
NLFP-100	0	--	--	1/31/00	2/10/00	
NLFP-101	753	-26.7	-4.78	2/10/00	2/24/00	
NLFP-102	1,104	-8.6	-2.77	2/24/00	3/14/00	
NLFP-103	825	-20.5	-4.42	3/14/00	3/27/00	
NLFP-104	499	-12.8	-3.44	3/27/00	4/6/00	
NLFP-105	748	-22.8	-4.99	4/6/00	4/19/00	
NLFP-106	1,005	-11.8	-2.82	4/19/00	5/3/00	
NLFP-107	22	-27.5	-4.35	5/3/00	5/24/00	
NLFP-108	1,758	-29.9	-5.07	5/24/00	6/8/00	

[1] Data not used because sample was a duplicate, a control, or evaporated due to lack of oil layer

[2] Collector overflowed



Appendix 2. Isotope and chemical profiles with depth in the three test wells at the Norman Landfill, Norman, Oklahoma. Note that the isotopic δ values, not the calculated offsets from the LMWL, are shown in the profiles. The depth scale on the plots is in meters based on the North American Vertical Datum of 1988. The land surface elevation is 330.88 meters at the Plume site, 330.54 meters at the Slough Bank site, and 330.30 meters at the Control site. The plots show changes in the thickness of the recharge layer at each site. There is a set of plots for each sampling period; the Slough Bank and Control wells were sampled from May 1998 to May 2000, and the Plume well was sampled from October 1998 to May 2000.

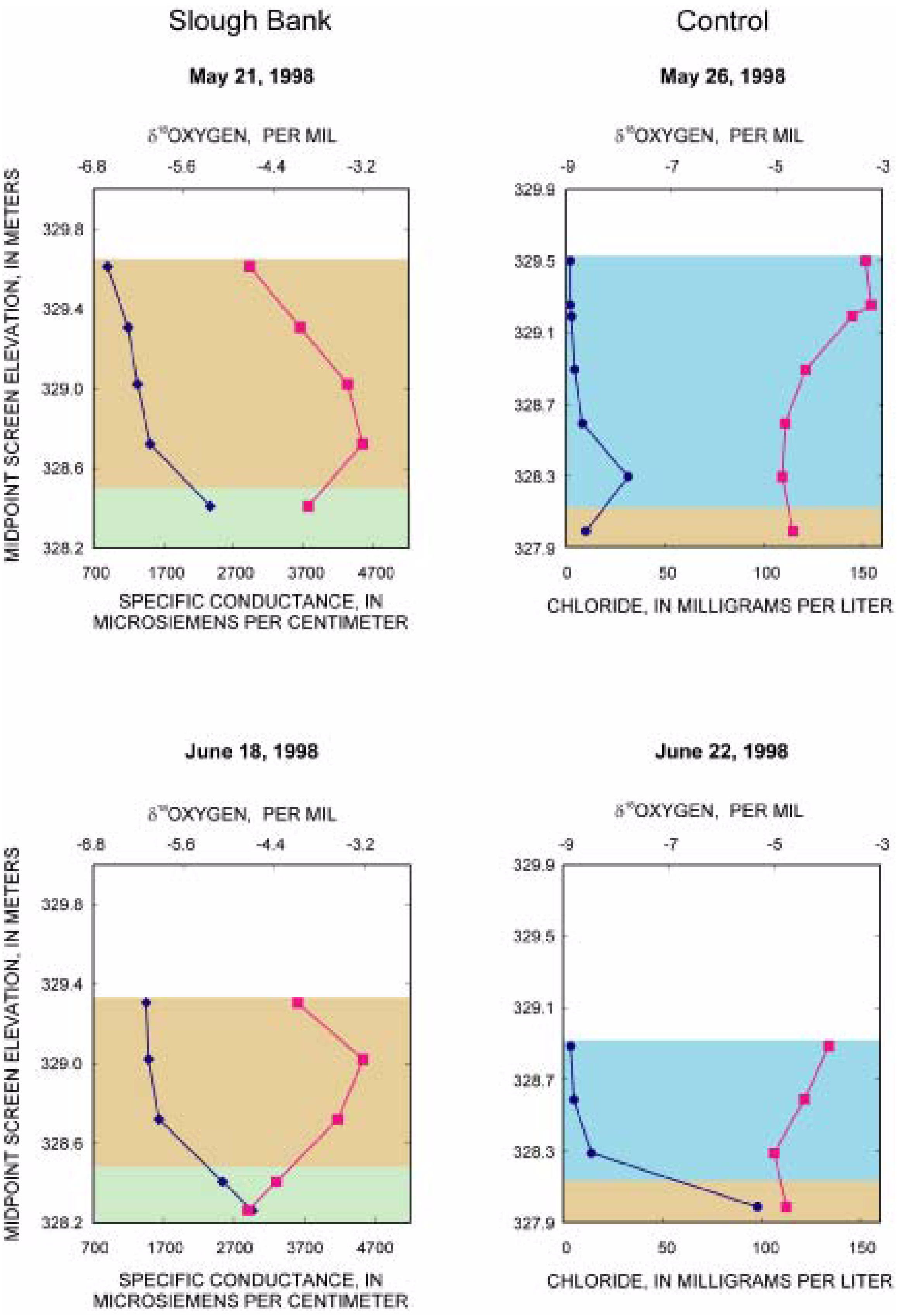

Slough Bank
Control
May 21, 1998
May 26, 1998
δ^{18}OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
MIDPOINT SCREEN ELEVATION, IN METERS
δ^{18}OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER
June 18, 1998
June 22, 1998

Figure 2.1.

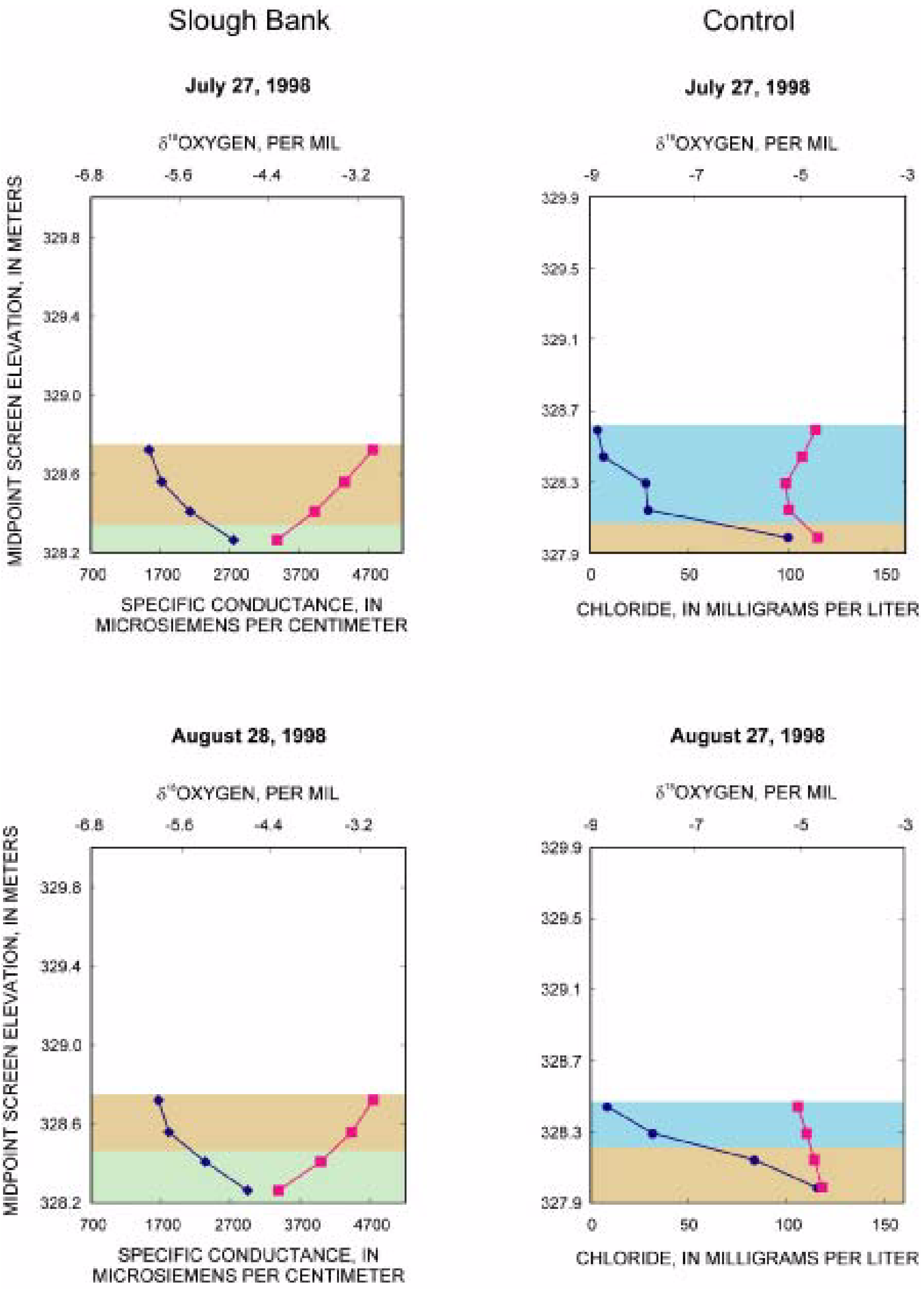

Slough Bank
Control
July 27, 1998
July 27, 1998
August 28, 1998
August 27, 1998
δ18OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
-9
-7
-5
-3
MIDPOINT SCREEN ELEVATION, IN METERS
329.8
329.4
329.0
328.6
328.2
329.9
329.5
329.1
328.7
328.3
327.9
700
1700
2700
3700
4700
0
50
100
150
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.2.

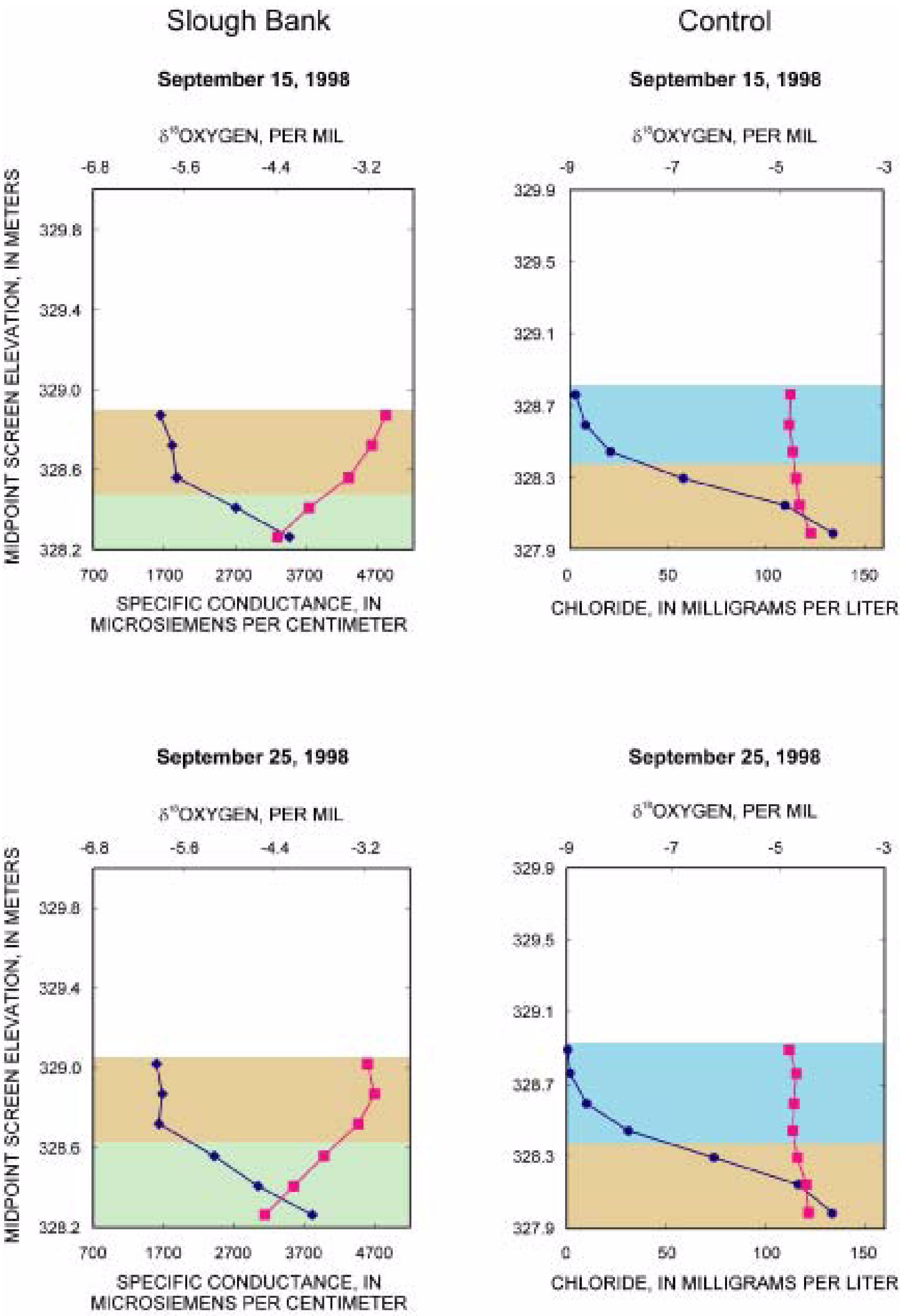

Slough Bank
Control
September 15, 1998
September 15, 1998
δ^{18}OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
-9
-7
-5
-3
MIDPOINT SCREEN ELEVATION, IN METERS
329.8
329.4
329.0
328.6
328.2
329.9
329.5
329.1
328.7
328.3
327.9
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER
September 25, 1998
September 25, 1998

Figure 2.3.

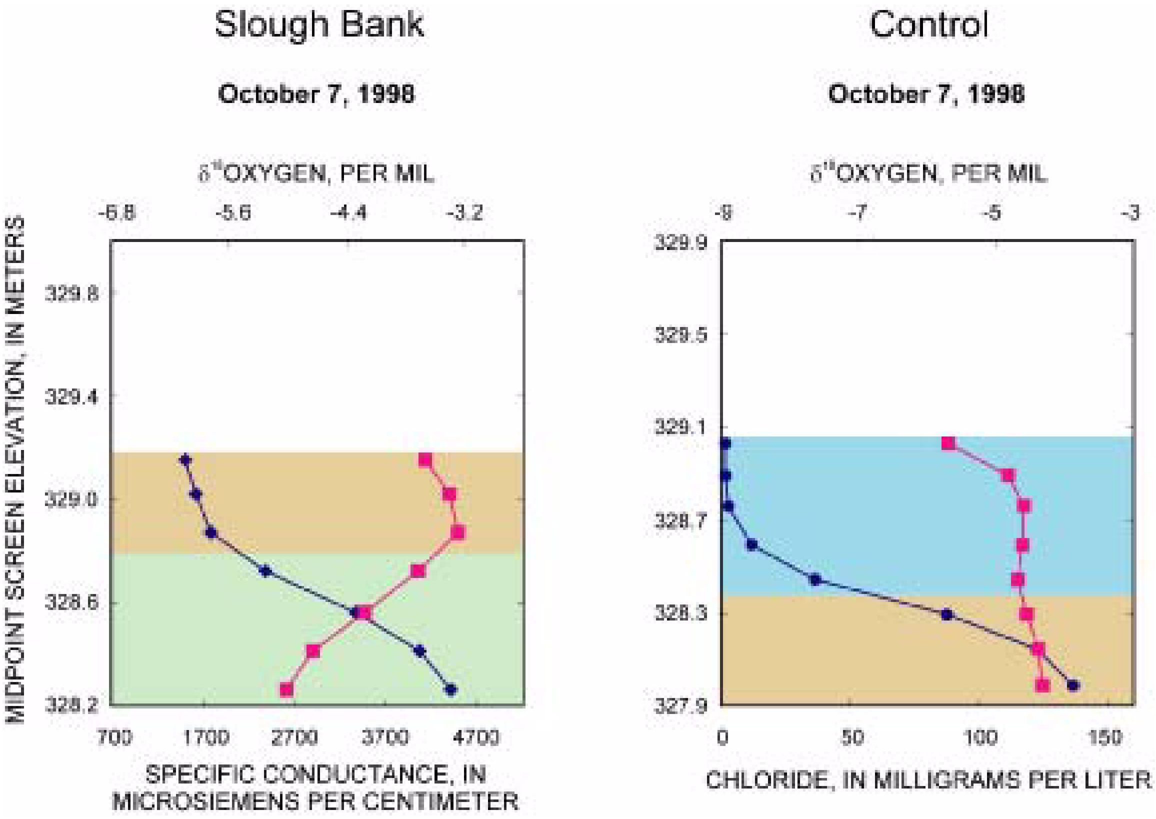

Slough Bank
October 7, 1998
δ18OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
MIDPOINT SCREEN ELEVATION, IN METERS
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
October 7, 1998
δ18OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.4.

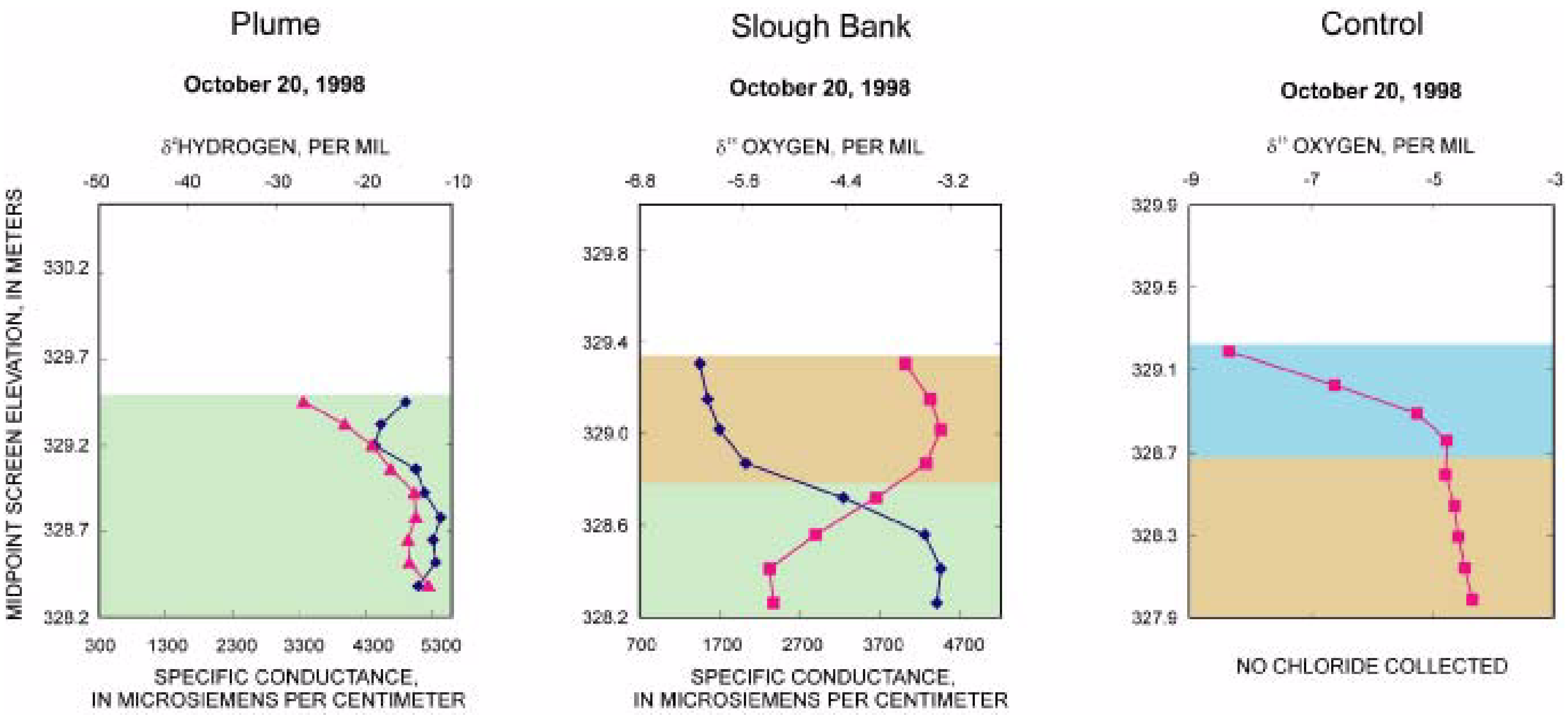

Plume
October 20, 1998
δ2HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE,
IN MICROSIEMENS PER CENTIMETER
Slough Bank
October 20, 1998
δ18 OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE,
IN MICROSIEMENS PER CENTIMETER
Control
October 20, 1998
δ18 OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
NO CHLORIDE COLLECTED

Figure 2.5.

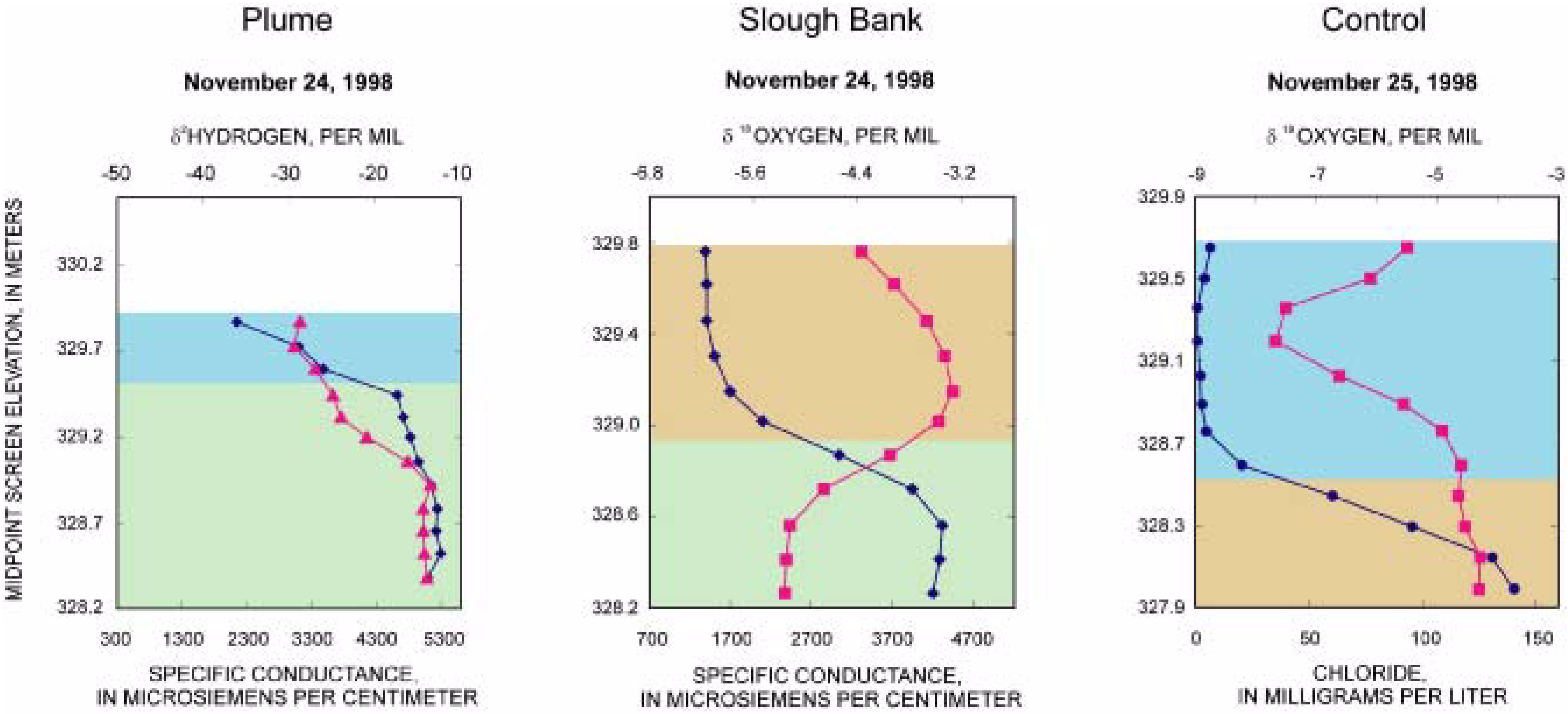

Plume
November 24, 1998
δ²HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
November 24, 1998
δ¹⁸OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
November 25, 1998
δ¹⁸OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.6.

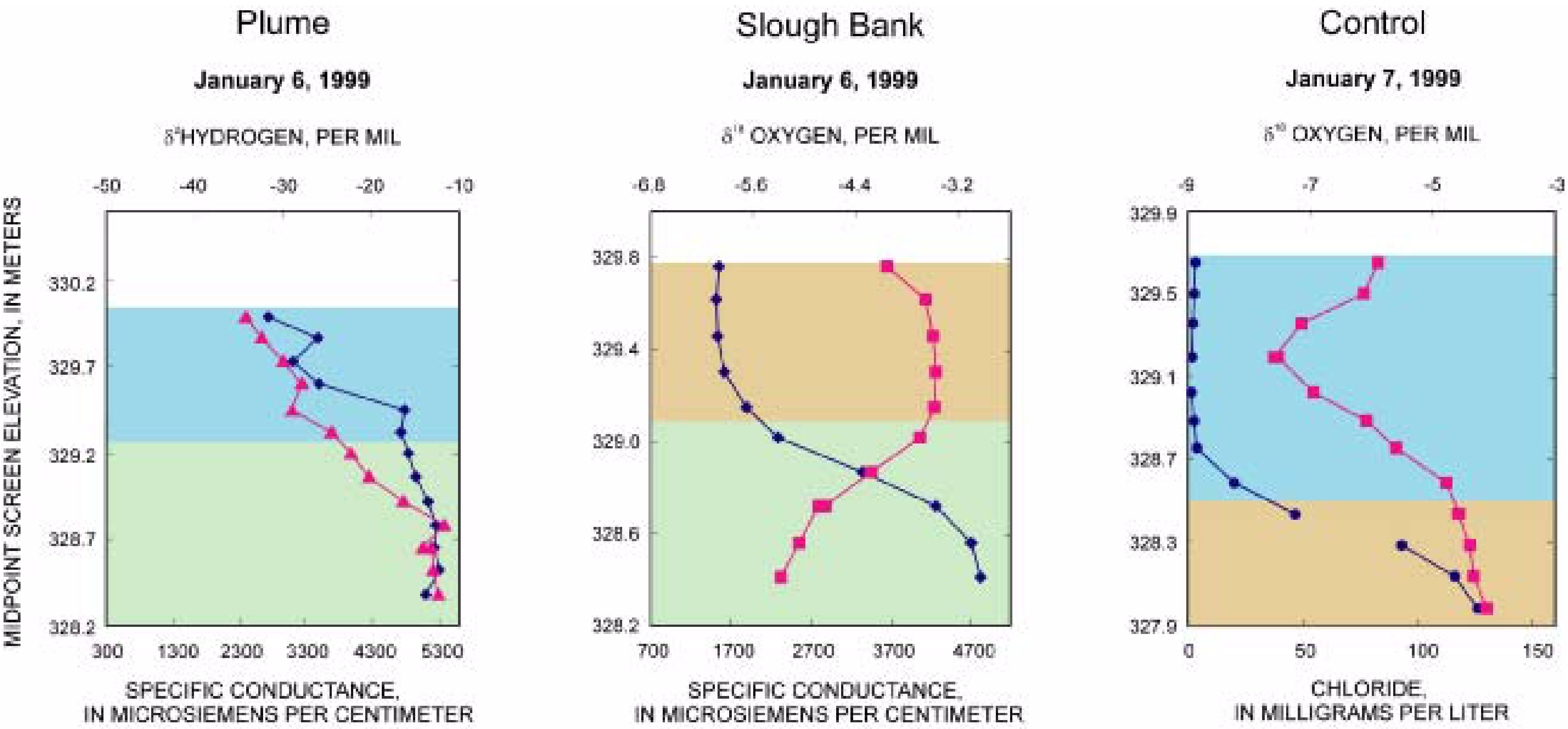

Plume
January 6, 1999
δ²HYDROGEN, PER MIL
-50
-40
-30
-20
-10
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
MIDPOINT SCREEN ELEVATION, IN METERS
Slough Bank
January 6, 1999
δ¹⁸ OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
January 7, 1999
δ¹⁸ OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.7.

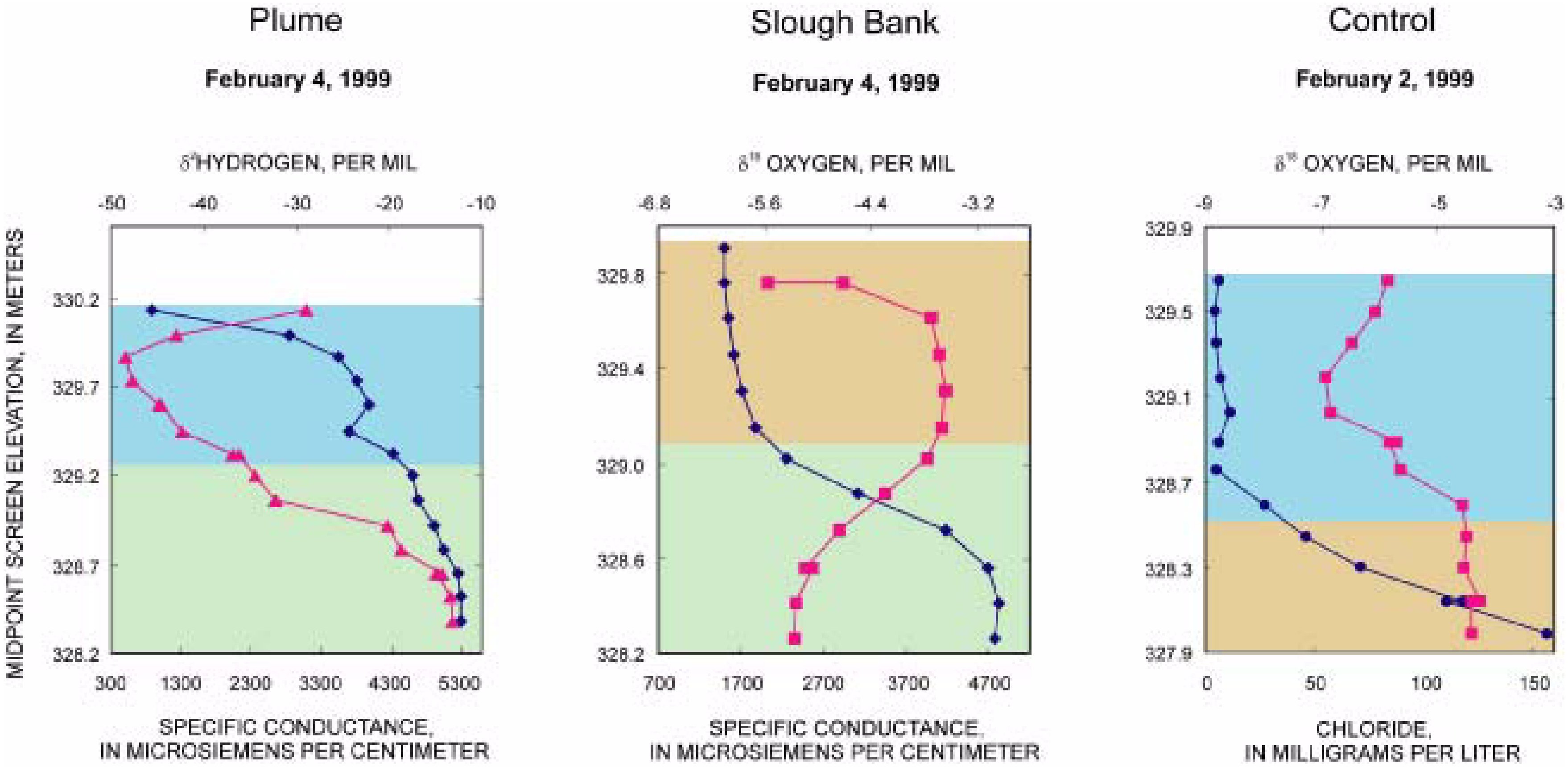

Plume
February 4, 1999
δ²HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
February 4, 1999
δ¹⁸ OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
February 2, 1999
δ¹⁸ OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.8.

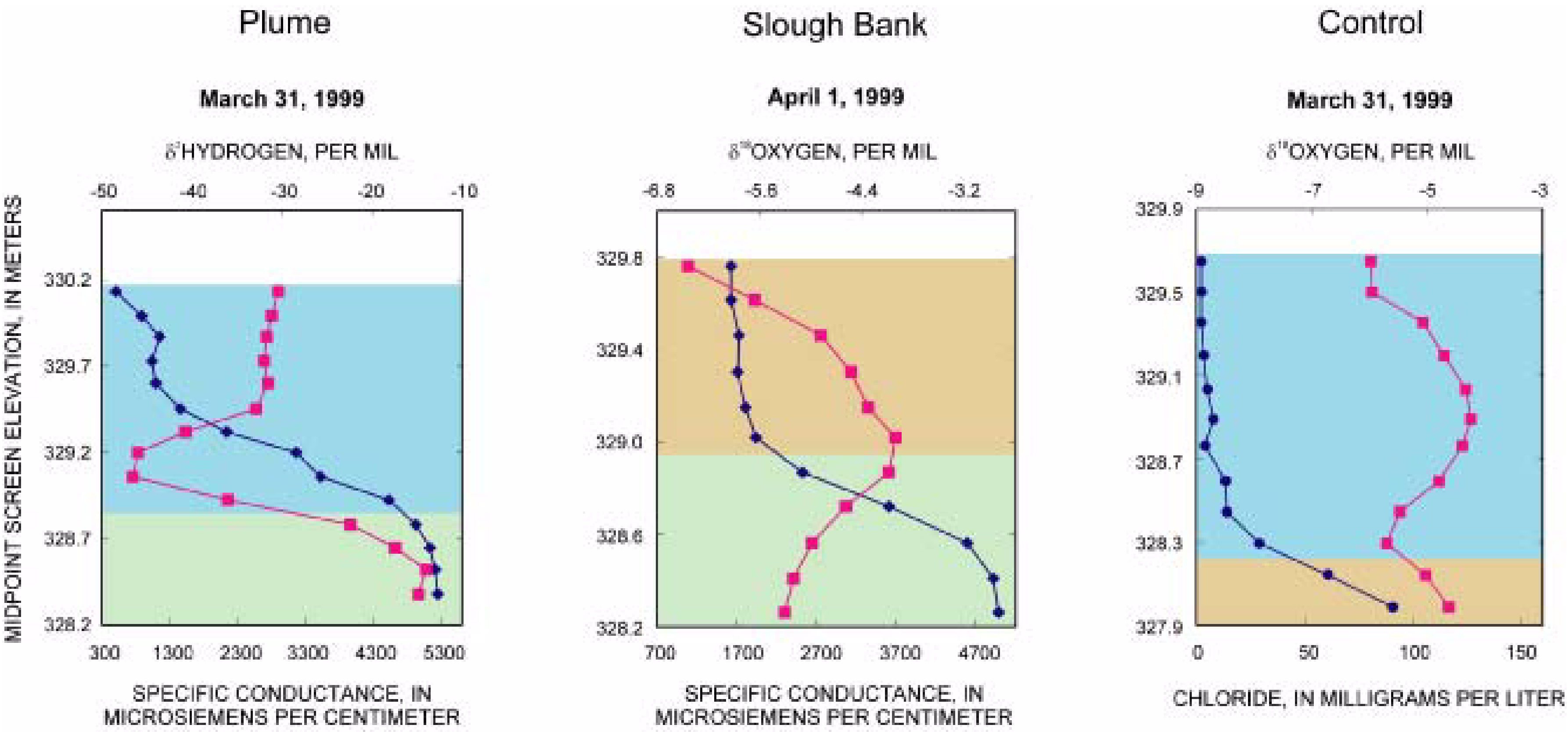

Plume
March 31, 1999
δ^{2}HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
April 1, 1999
δ^{18}OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
March 31, 1999
δ^{18}OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.9.

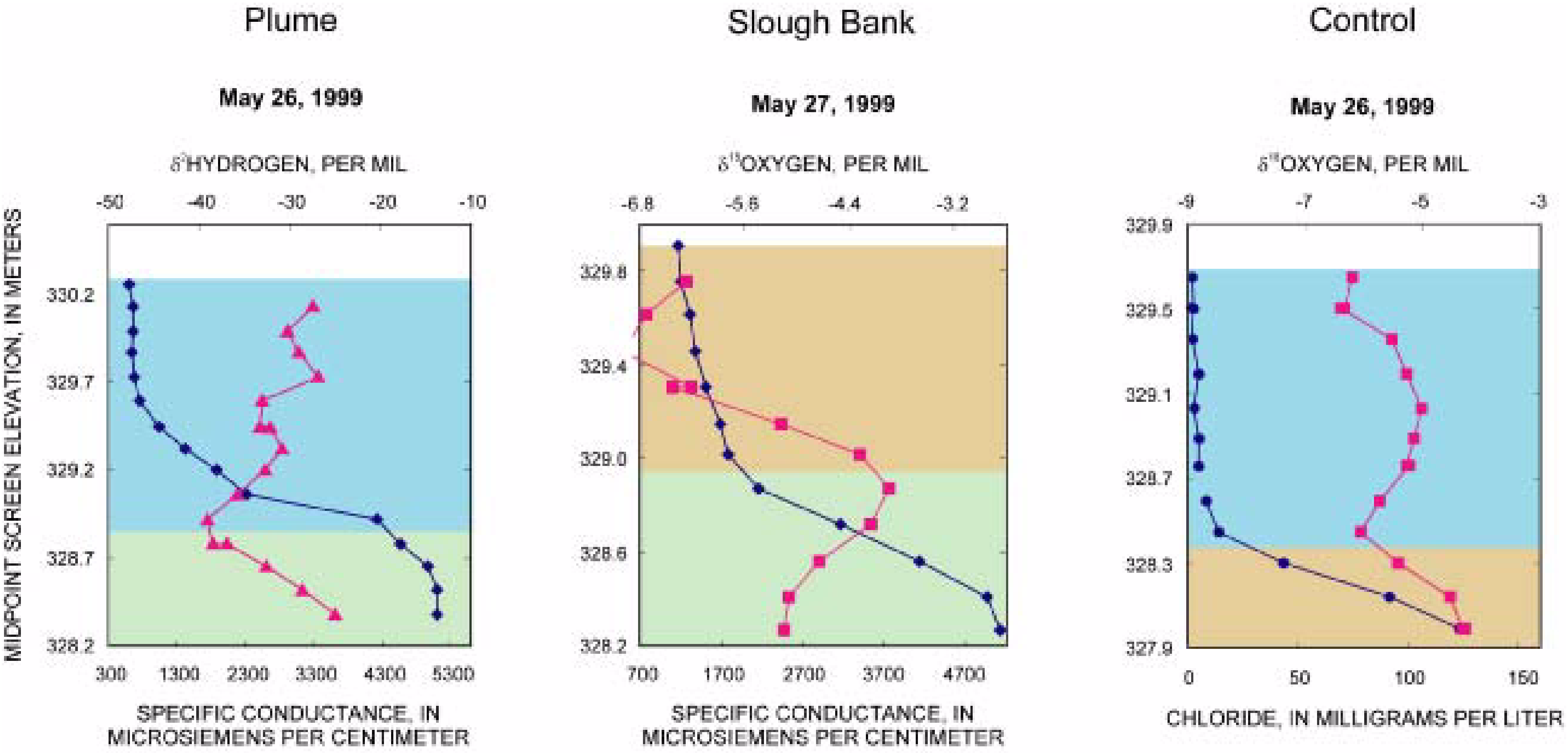
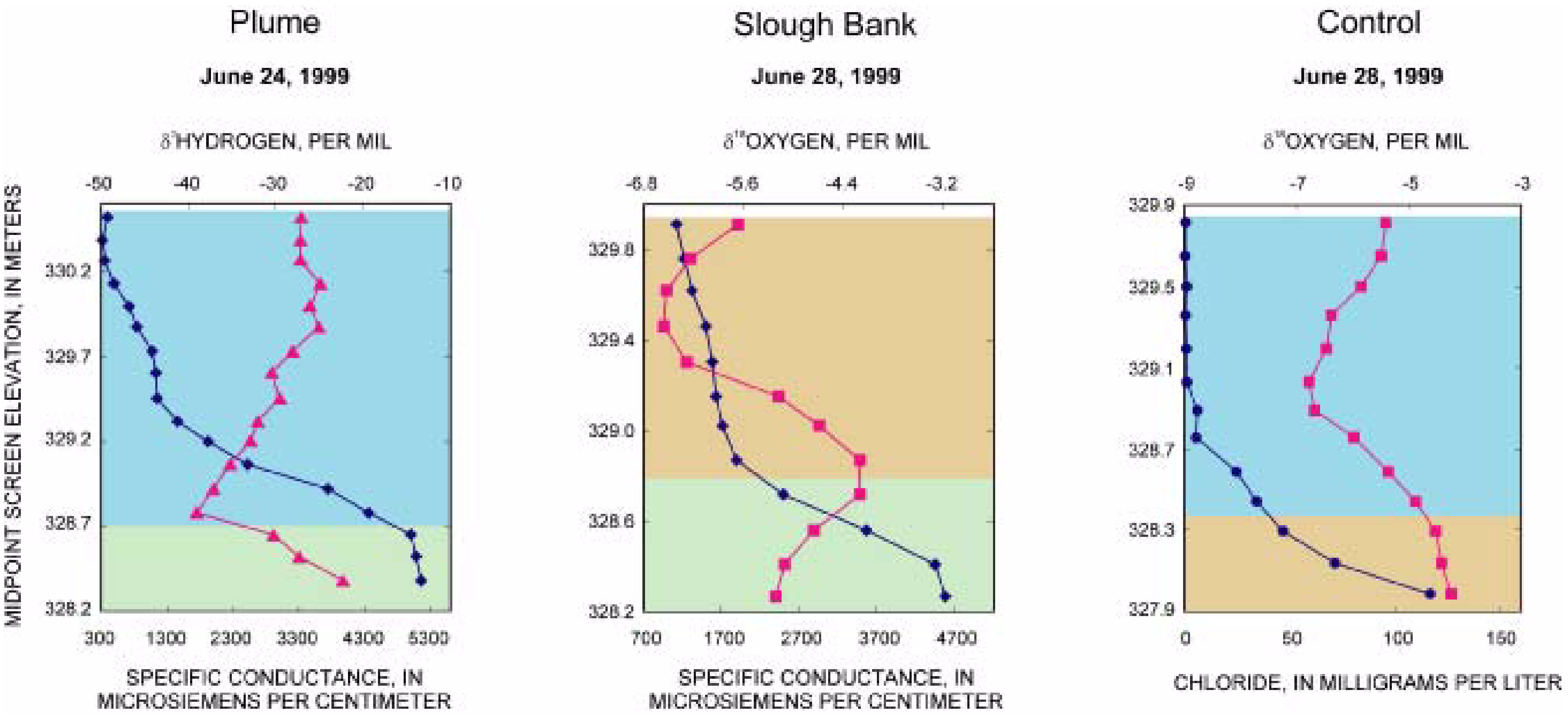

Plume
May 26, 1999
δ²HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
May 27, 1999
δ¹⁸OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
May 26, 1999
δ¹⁸OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.10.



Plume

June 24, 1999

Slough Bank

June 28, 1999

Control

June 28, 1999

Figure 2.11.

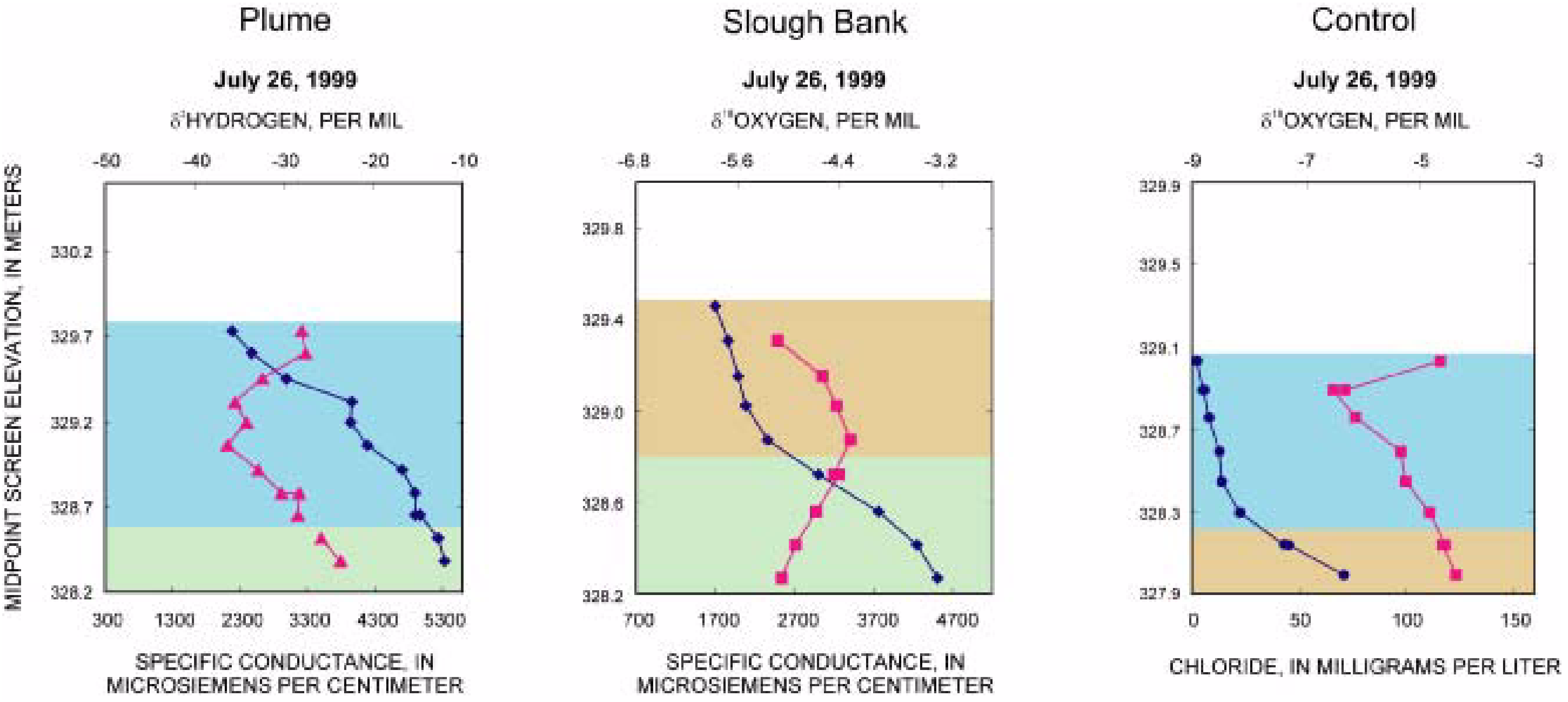

Plume
July 26, 1999
δ²HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
July 26, 1999
δ¹⁸OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
July 26, 1999
δ¹⁸OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.12.

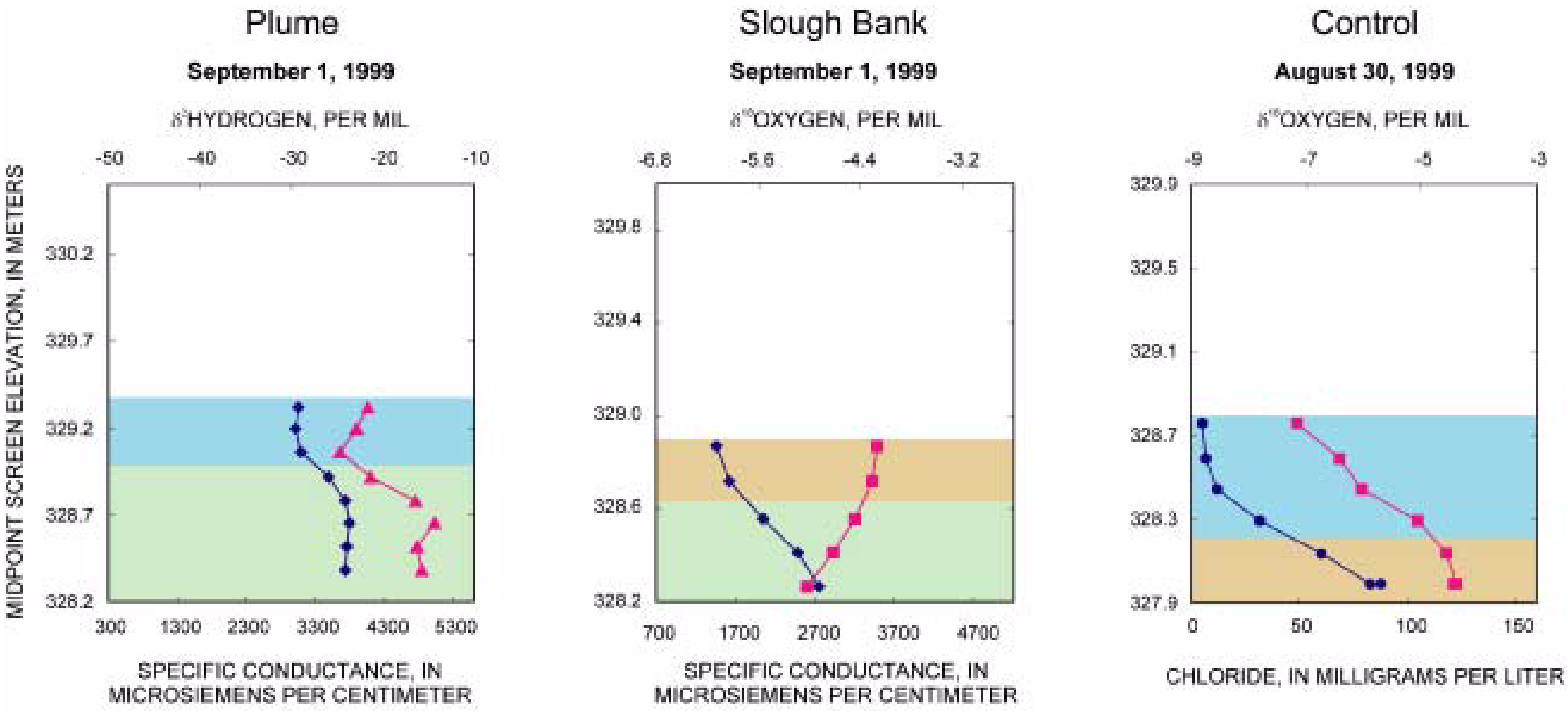

Plume
September 1, 1999
δ^{2}HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
September 1, 1999
δ^{18}OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
August 30, 1999
δ^{18}OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.13.

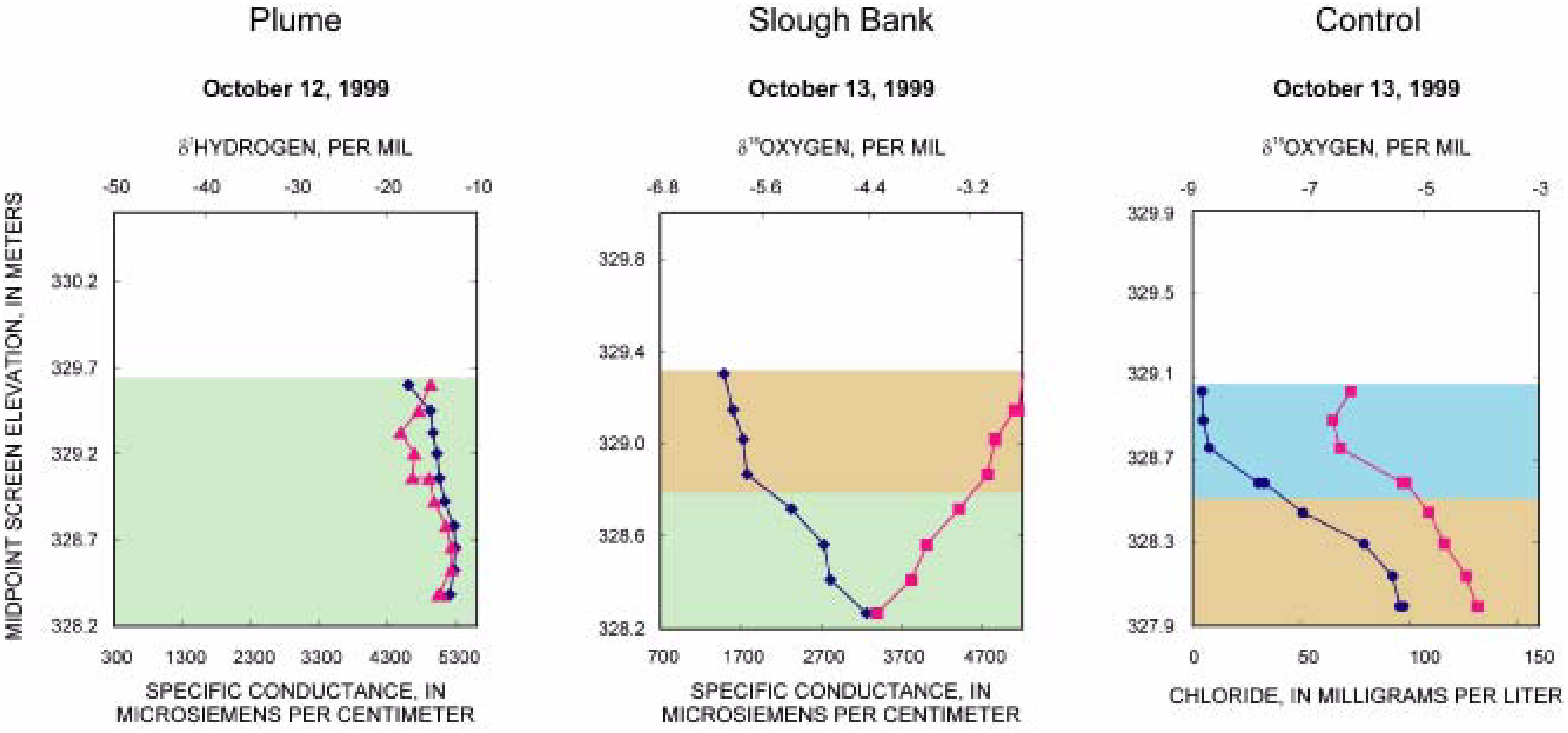

Plume
October 12, 1999
δ^{2}HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
October 13, 1999
δ^{18}OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
October 13, 1999
δ^{18}OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.14.

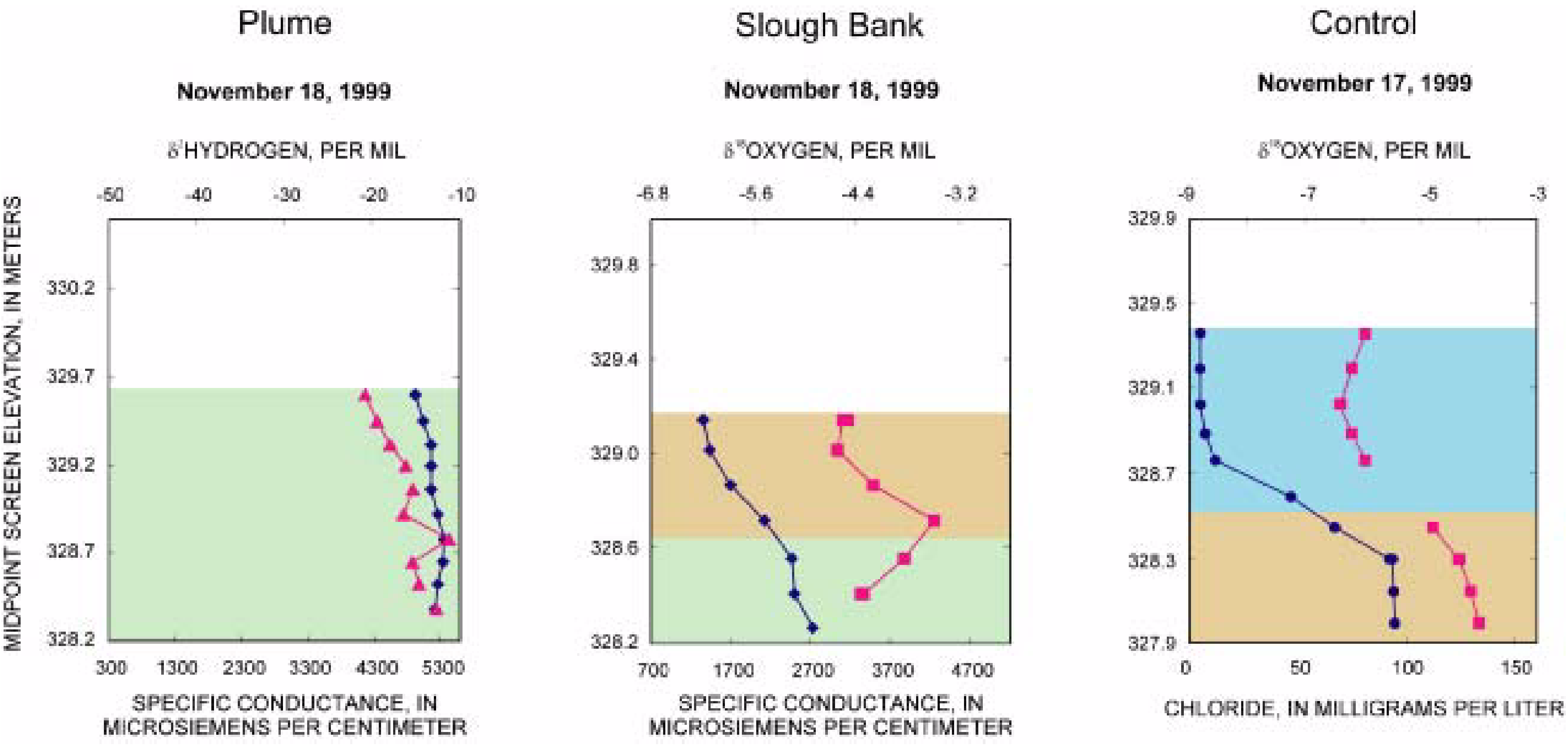

Plume
November 18, 1999
δ^{2}HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
November 18, 1999
δ^{18}OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
November 17, 1999
δ^{18}OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.15.

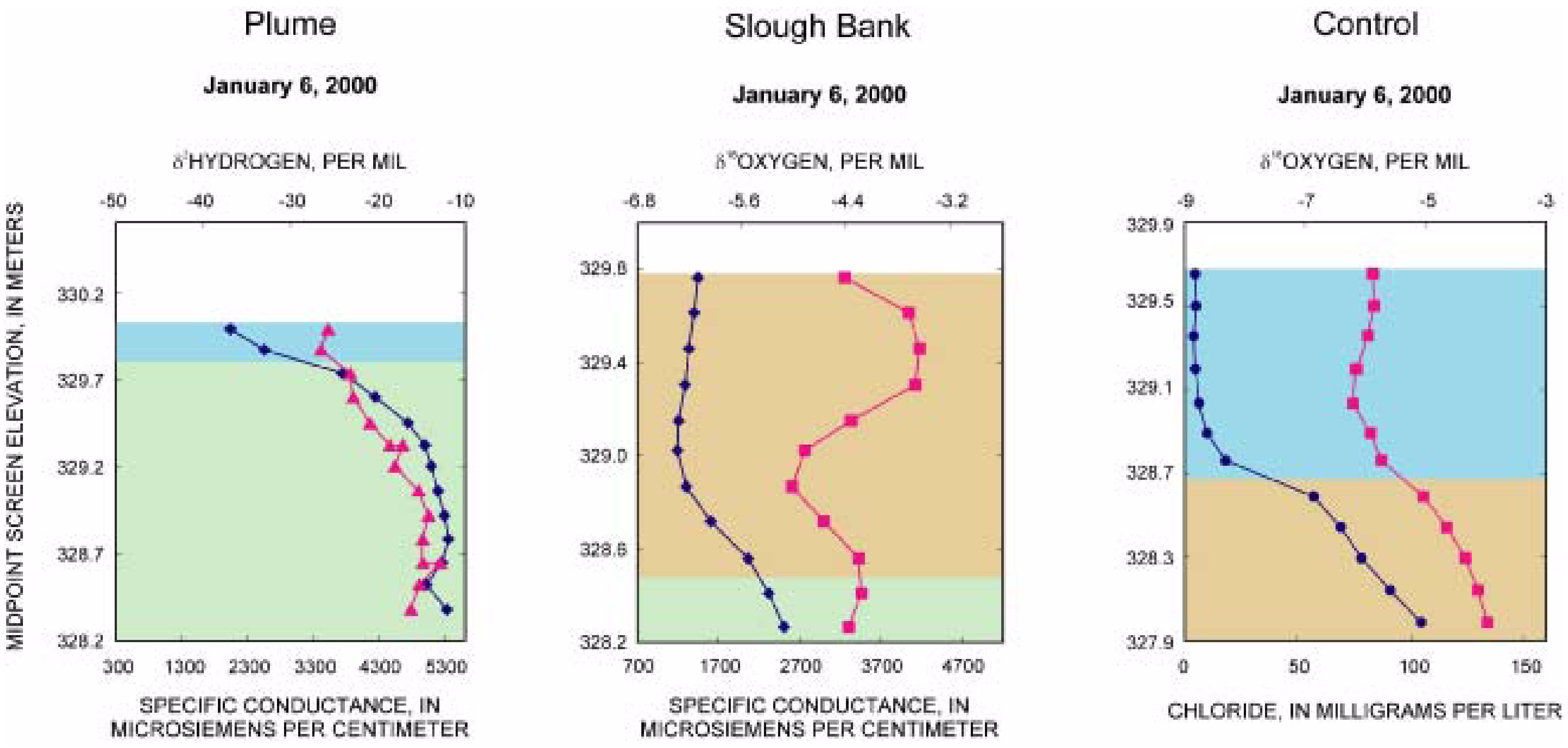

Plume
January 6, 2000
δ²HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
January 6, 2000
δ¹⁸OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
January 6, 2000
δ¹⁸OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.16.

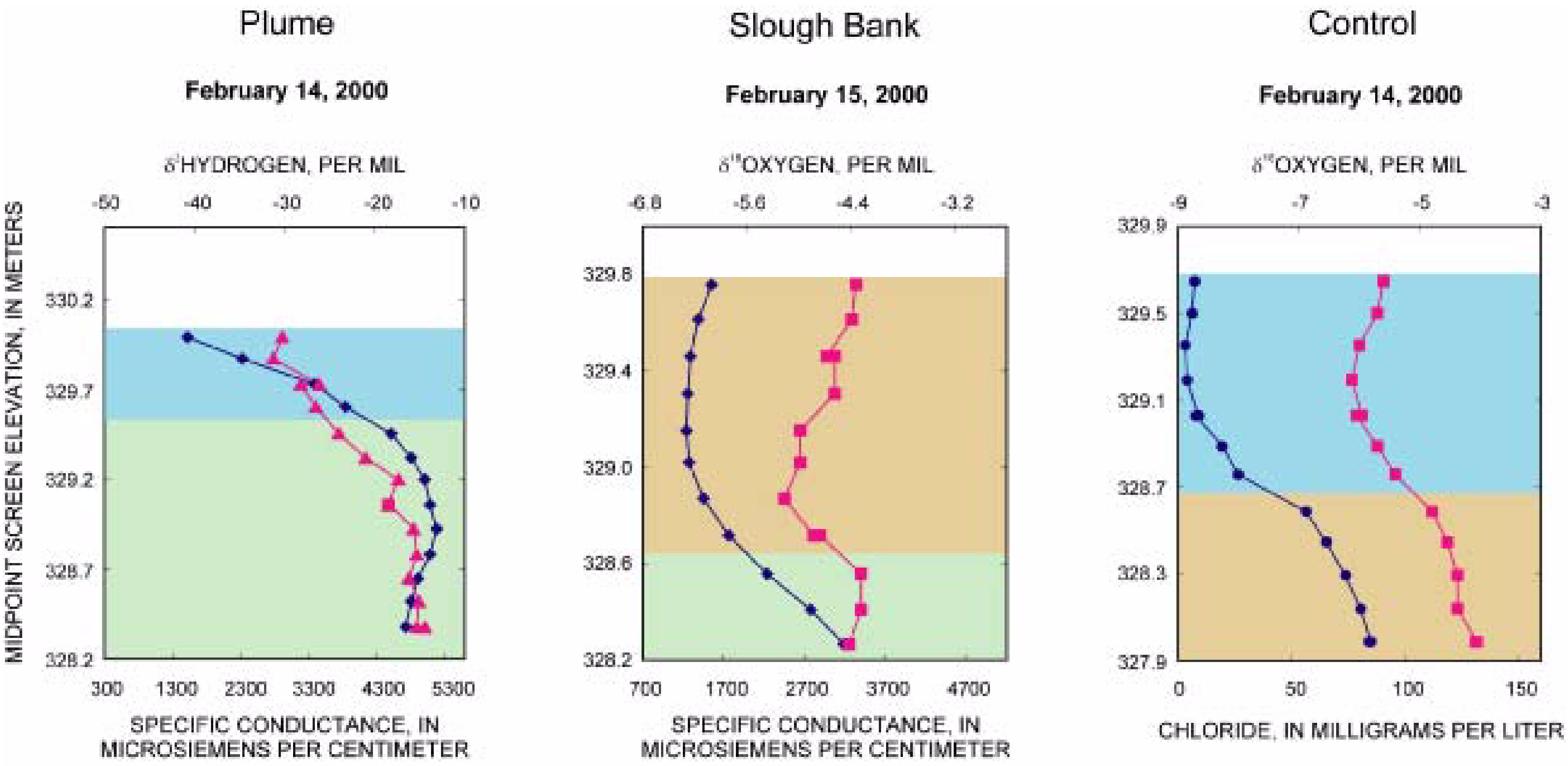

Plume
February 14, 2000
δ^{2}HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
February 15, 2000
δ^{18}OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
February 14, 2000
δ^{18}OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.17.

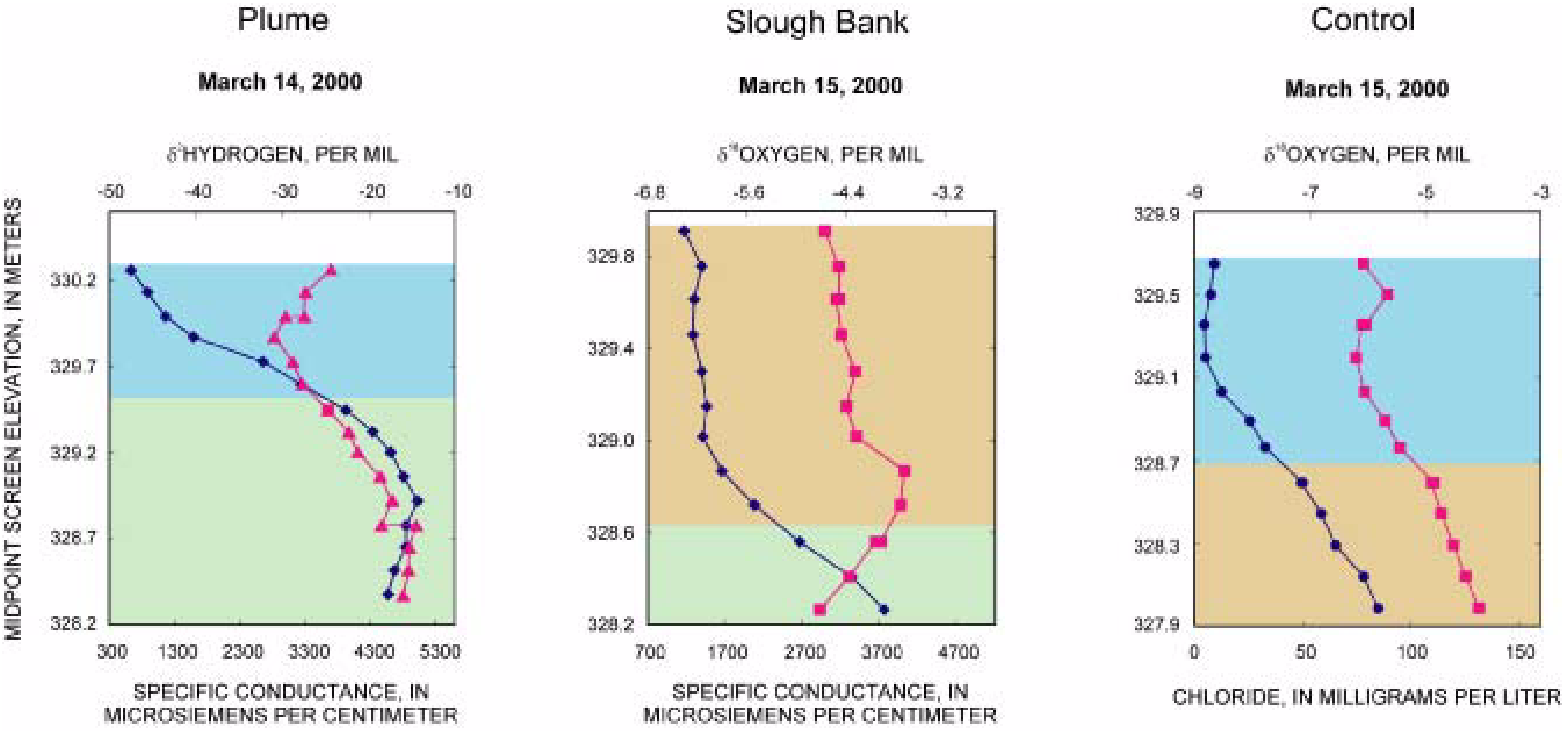

Plume
March 14, 2000
δ²HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
March 15, 2000
δ¹⁸OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
March 15, 2000
δ¹⁸OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.18.

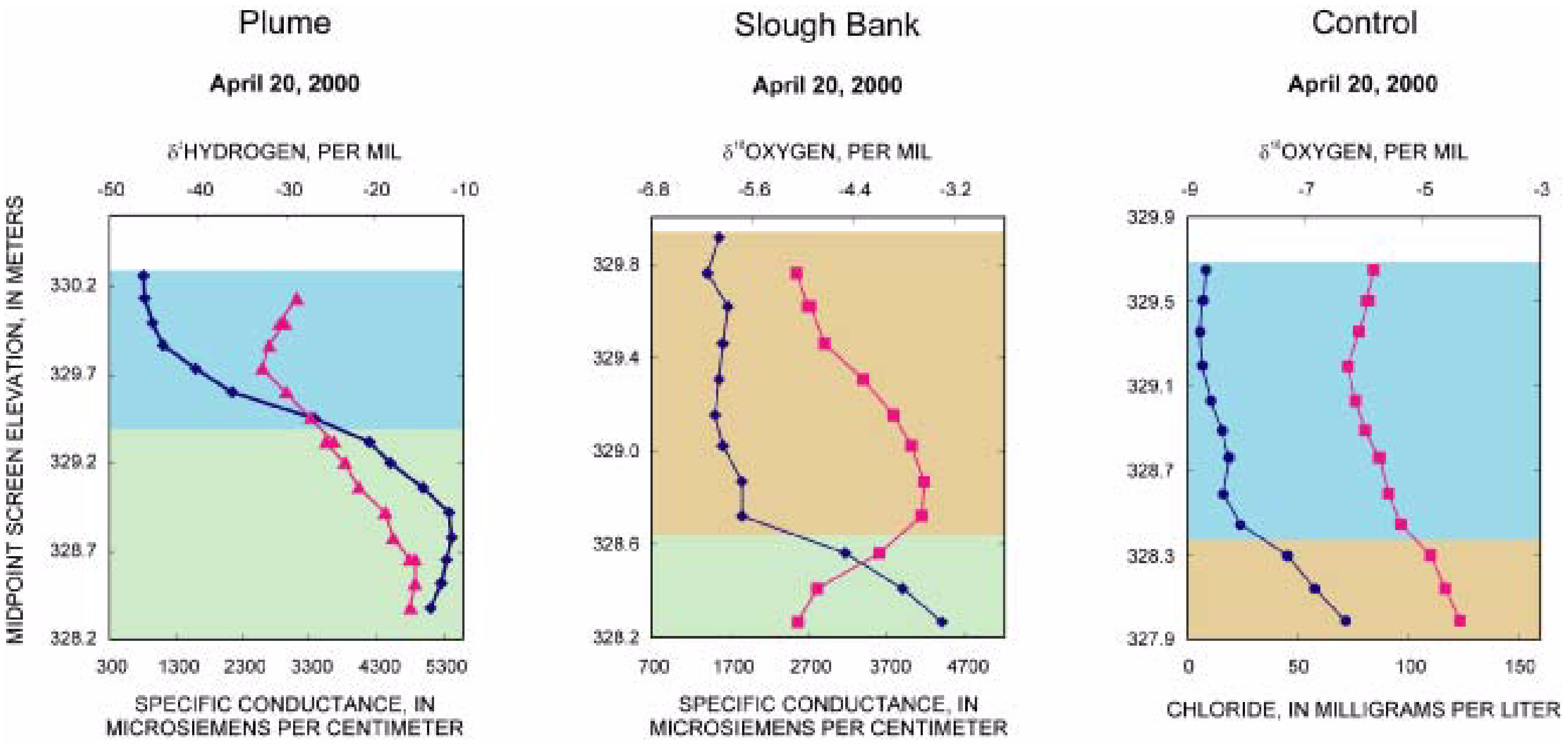

Plume
April 20, 2000
δ^{2}HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
April 20, 2000
δ^{18}OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
April 20, 2000
δ^{18}OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.19.

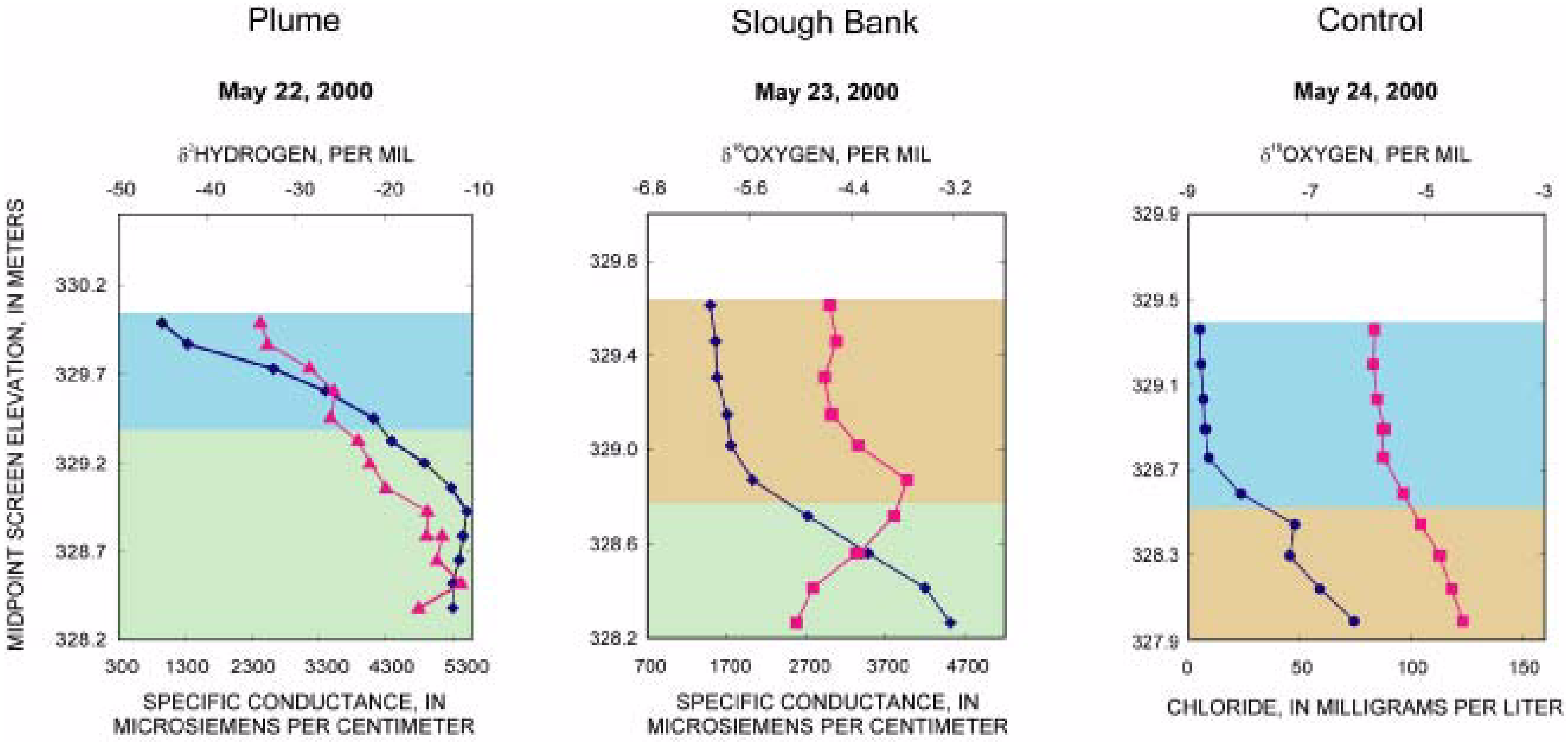

Plume
May 22, 2000
δ²HYDROGEN, PER MIL
-50
-40
-30
-20
-10
MIDPOINT SCREEN ELEVATION, IN METERS
330.2
329.7
329.2
328.7
328.2
300
1300
2300
3300
4300
5300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Slough Bank
May 23, 2000
δ¹⁸OXYGEN, PER MIL
-6.8
-5.6
-4.4
-3.2
329.8
329.4
329.0
328.6
328.2
700
1700
2700
3700
4700
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
Control
May 24, 2000
δ¹⁸OXYGEN, PER MIL
-9
-7
-5
-3
329.9
329.5
329.1
328.7
328.3
327.9
0
50
100
150
CHLORIDE, IN MILLIGRAMS PER LITER

Figure 2.20.