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VARIABILITY OF NITRATE LOADING AND DETERMINATION OF MONITORING FREQUENCY FOR A SHALLOW SANDY AQUIFER, ARENA, WISCONSIN : FINAL REPORT

VARIABILITY OF NITRATE LOADING AND DETERMINATION OF MONITORING FREQUENCY FOR A SHALLOW SANDY AQUIFER, ARENA, WISCONSIN

Final Report to the Wisconsin Department of Natural Resources

by

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Chris Johnson also assisted with piezometer installation and provided the equipment shelter that housed the ISCO sampler and datalogger. Kim Cates, of the Wisconsin Geological and Natural History Survey, assisted with maintenance of the water-level monitoring system from October 1997 to June 1998.

The Wisconsin Department of Natural Resources provided funding for this project through the Groundwater Management Practice Monitoring Program, which receives appropriations from the Groundwater Account.

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INTRODUCTION

Project Background

Nitrate contamination has long been known to be a problem in Wisconsin's sandy aquifers with shallow depth to groundwater (Jackson and others, 1987). Recent data suggest that 10-20 percent of domestic wells in agricultural counties across the state exceed the drinking water standard of 10 mg/l NO_3-N (Kraft, 1994); in Dane County 24 percent of rural wells exceed this standard (Bridson and others, 1994). Shallow, sandy aquifers are especially vulnerable to nitrate contamination due to rapid infiltration and the limited attenuation capability of these coarse-textured soils. In areas where sandy soils are used for crop production, nitrate contamination is common. For example, 34 percent of wells in the Lower Wisconsin River Valley exceed the 10 mg/l NO_3-N standard (Cates and Madison, 1992). Management of agricultural nitrogen inputs is becoming a growing concern; the Wisconsin Department of Agriculture, Trade, and Consumer Protection (DATCP) is considering new regulations aimed at managing nitrogen applications. In order to determine how various agricultural management practices impact groundwater, we first need to identify the temporal variability in nitrate concentrations reaching the saturated zone. Most groundwater monitoring projects assume that monthly or quarterly samples are adequate to characterize nitrate concentrations in groundwater, yet this assumption has not been tested.

Purpose and Scope

The objectives of this project were 1) to determine the temporal variability in nitrate concentrations in shallow, sandy aquifers, 2) to define the relationship between recharge and groundwater nitrate concentrations, and 3) to develop recommendations concerning monitoring frequency for such aquifers. Specifically we hoped to examine the distsribution of nitrate and cloride across hydrographs generated by rainfall or other climatic events

FIELD SETTING AND METHODS

An existing research site, in the Lower Wisconsin River Valley, provided a controlled setting where we could explore the temporal variability of nitrate loading in shallow sandy aquifers. The site was established to investigate the effects of ridge tillage on the movement of agrichemicals in the unsaturated zone under corn and soybeans (Lowery and McSweeney, 1992; Fermanich, 1995) and was ideally suited for monitoring of nitrate in the saturated zone.

Geologic Setting

The research site, located north of Arena, Wisconsin, in eastern Iowa County, is within the "Driftless" or unglaciated portion of the Lower Wisconsin River Basin (figure 1). The bedrock geology of the basin consists of Precambrian crystalline rock overlain by a thick sequence of relatively-flat-lying Cambrian sandstone, shale, and Ordovician dolomite. These sedimentary strata dip and thicken to the southwest (Hindall and Borman, 1974). During Late Pleistocene time, meltwater streams cut deeply into Paleozoic bedrock and deposited a nearly 200 ft thick sequence of sand and gravel in the Wisconsin River Valley; lake sediments were deposited in many of the tributary valleys. A thin loess cover blankets the bedrock uplands.

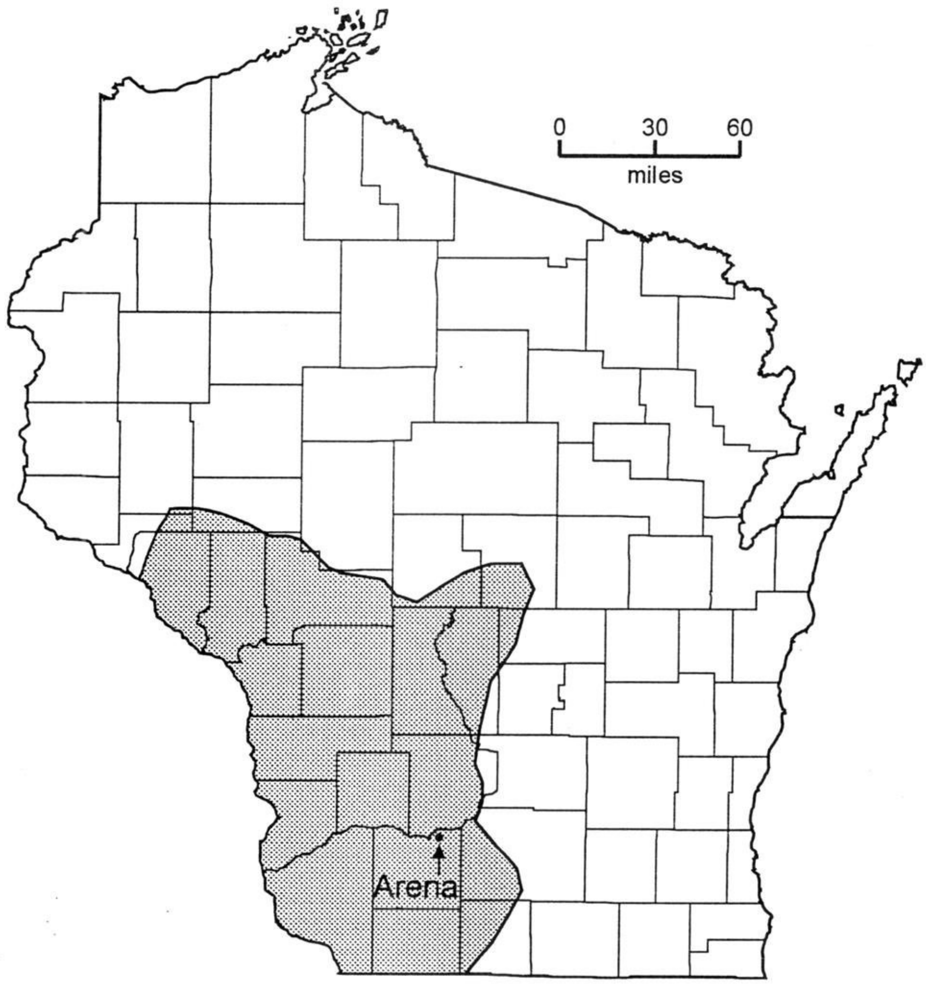

Figure 1. Location map showing "Driftless" area (shaded gray) and location of the Arena research site.

Hydrogeologic Setting

The sand and gravel of the Wisconsin River Valley form a productive aquifer with expected well yields of over 1000 gpm (Hindall and Borman, 1974). Over much of basin, groundwater follows short flow paths from upland recharge areas to discharge areas along the Wisconsin River and its tributaries. The area receives about 32.1 in/yr of precipitation (Hindall and Borman, 1974) of which approximately 19.8 inches arrives during the growing season from April to September.

Site Description

The 7-acre research site (figure 2), established in June of 1989 by Lowery and McSweeney (1994), is typical of agricultural production areas in the Lower Wisconsin River Valley. Soils consist of medium to coarse-textured Sparta sands (Iowa County Soil Survey) that are excessively well-drained and have limited water-holding capacity. Given these soil characteristics, the site, like much of the land under cultivation in the Lower Wisconsin River Valley, requires supplemental irrigation to provide water to meet crop needs. Depth to groundwater is approximately 8 to 12 feet. Previous measurements indicate that groundwater under the site flows to the north-northeast at a rate of 1.3 ft/day (Fermanich, unpublished data) and ultimately discharges to the Wisconsin River.

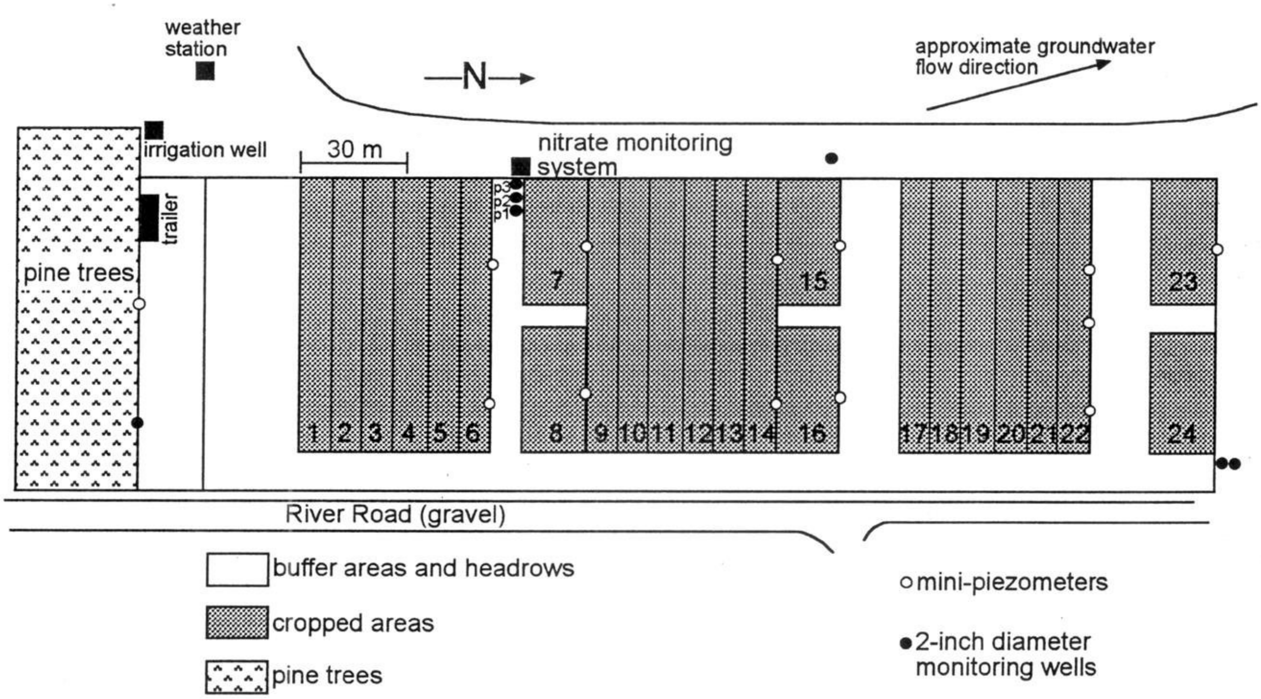

Figure 2. Schematic map of field research site Arena, Wisconsin (modified from Fermanich, 1995). Piezometers p1, p2, and p3 were installed for the nitrate monitoring project.

Agricultural Management Methods

Field research at this site was initiated in order to investigate the movement of agrichemicals in the unsaturated zone under various irrigation schemes and tillage practices. Corn, soybean, and potato production at the site represents a land-use that is typical of shallow sandy aquifers throughout the state.

During the time period of this study (1996, 1997, and 1998 growing seasons) the site was planted primarily in field corn although sweet corn, potatoes, and soybeans were grown in some plots. Details of cropping history are summarized in Table 1. Some nitrogen required for crop growth is applied at planting; one or two additional applications during the growing season provide the balance of the required N. Nitrogen applications at the site were designed to meet University recommendations for crops under production. Details on the timing and rates of nitrogen application during the time period of this study are included in Table 2.

Site Instrumentation and Data Collection

Existing instrumentation

Instrumentation installed by previous investigators included four monitoring wells, a 65-ft deep irrigation well, a network of mini-piezometers, an automated weather station, and a soil moisture monitoring and sampling network (figure 2). The automated weather station, maintained by Bill Bland of the UW-Soils Science Department as part of Wisconsin's automated agricultural weather network, recorded hourly data on total precipitation; average solar radiation; average air temperature; average relative humidity; average soil temperature at depths of 2, 4, and 20 inches; wind speed and direction; solar radiation; and average dew temperature. These data are available at http://bob.soils.wisc.edu/wimnext/ (station name SPR).

Table 1. Cropping history during 1996-1998 growing seasons*.

	Field Corn	Sweet Corn	Potatoes	Soybeans
1996	1-6, 9-14, 17-22	7, 16, 24	none	8, 15, 23
1997	1-6, 9-24	none	7, 8	none
1998	1-4, 7&8, 11-14, 17-22	5&6, 9&10	15&16	23&24

* see figure 2 for plot numbers

Table 2. Timing and rates of nitrogen application during the 1996-1998 growing seasons.*

Field Corn		Sweet Corn		Potatoes		Soybeans	
5/2/96	18 lb/A	5/2/96	18 lb/A	not grown		no N applied	
6/14/96	90 lb/A	6/14/96	90 lb/A				
6/28/96	90 lb/A	6/28/96	90 lb/A				
6/3/97	6 lb/A	not grown		7/2/97	90 lb/A	not grown	
7/1/97	90 lb/A			7/14/97	90 lb/A		
7/14/97	90 lb/A						
5/19/98	6 lb /A	5/19/98	12 lb/A	6/5/98	100 lb/A	no N applied	
6/23/98	90 lb/A	6/23/98	90 lb/A	6/22/98	100 lb/A		
7/8/98	90 lb/A	7/8/98	90 lb/A				

*Application rates listed are lbs of N per acre

Nitrate Monitoring System

In Wisconsin, the majority of groundwater recharge occurs during spring snowmelt and, to a lesser extent, in fall once vegetation becomes dormant and evapotranspiration decreases. In sandy settings, intense summer thunderstorms can also contribute to recharge. The nitrate monitoring system was designed to assess variations in nitrate loading to the water table during the growing season. Monitoring was initiated in the spring of 1996 and continued until summer 1998; site visits were conducted approximately every two weeks over this time period. Instrumentation malfunctions in 1996 lead to an incomplete data set for both water levels and water quality. A relatively continuous record of water levels was collected from March 1997 to July 1998. Water-quality data are available during the entire 1997 growing season and during the spring recharge event of 1998.

A nest of three 2-inch piezometers was installed on the western edge of the research site in November of 1995 (figure 2) using the Wisconsin Geological and Natural History Survey's drill rig. Previously collected water-level data (Fermanich, unpublished data) indicated that the water table fluctuated from 8.3 to 12.1 ft below ground surface. Two shallow piezometers, with 5-ft screens, were installed across the zone of water-table fluctuations. The third piezometer was completed 5 ft below the shallow piezometers. Piezometers were installed though hollow-stem augers with an inner diameter of four inches. Construction details for the piezometers are shown in figure 3.

Water-level monitoring was initiated in the spring of 1996. Two 15-psi pressure transducers, wired to a datalogger, were used to monitor water levels in piezometers 2 (shallow) and 3 (deep). Water levels were sampled every 5 minutes and average hourly water levels were recorded in the data files. Data were downloaded at 2-week intervals and field-measured water levels were used to calibrate the transducer readings. Water-level data are included in the Appendix.

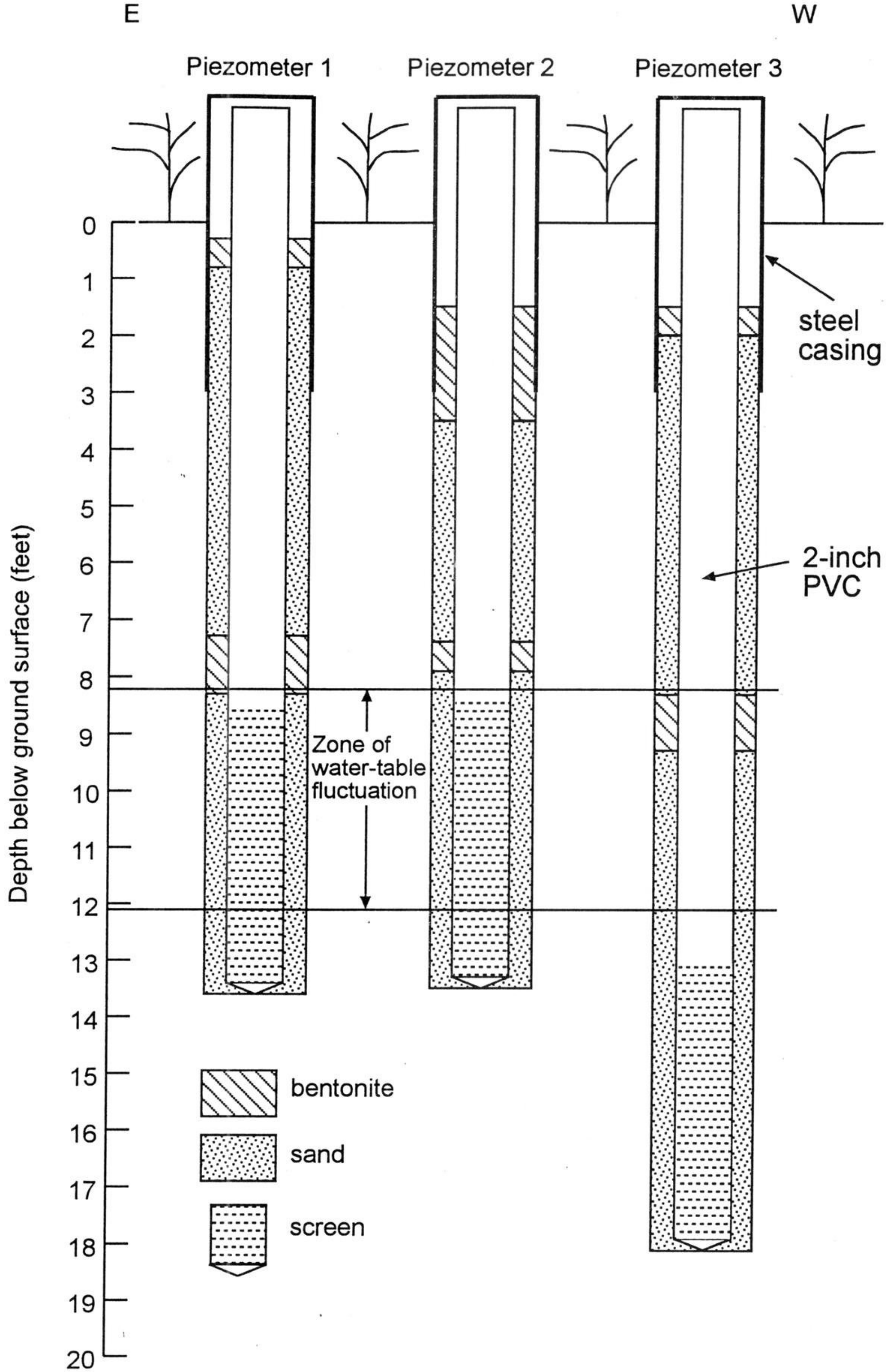

Figure 3. Construction diagram for piezometers installed for the nitrate monitoring project.

An ISCO automated sampler, powered by a 12-volt marine battery, was installed to collect samples from piezometer 1. Two sample collection schemes were used during the project. From the initiation of sampling until June 15, 1997, samples were collected every three hours and four samples were composited into a single bottle. From July 1, 1997 until the end of the project, samples were collected at 12-hour intervals during the growing season. A float device was used to keep the intake tubing six inches below the top of the water column in piezometer 1. The sampler automatically reversed the pump and purged the sample line after collection of each sample. Samples were retrieved at 2-week intervals and taken to the UW Soil and Plant Analysis Lab for nitrate and chloride analysis by ion chromatography. All sampling results are included in the Appendix.

RESULTS AND DISCUSSION

The primary objective of this project was to determine the temporal variability of nitrate loading to the water table in shallow, sandy aquifers. Data from the 1997 provide a relatively complete record of nitrate movement from March to December. These results are discussed in detail below. Results from 1996 and 1998 are less complete and are discussed only briefly. Figures 4, 5, and 9 summarize the water-quality, depth-to-groundwater, and precipitation data for 1996, 1997, and 1998 respectively. For each of these graphs, the major tick marks on the date axis are spaced every 28 days with minor tick marks every week (7 days).

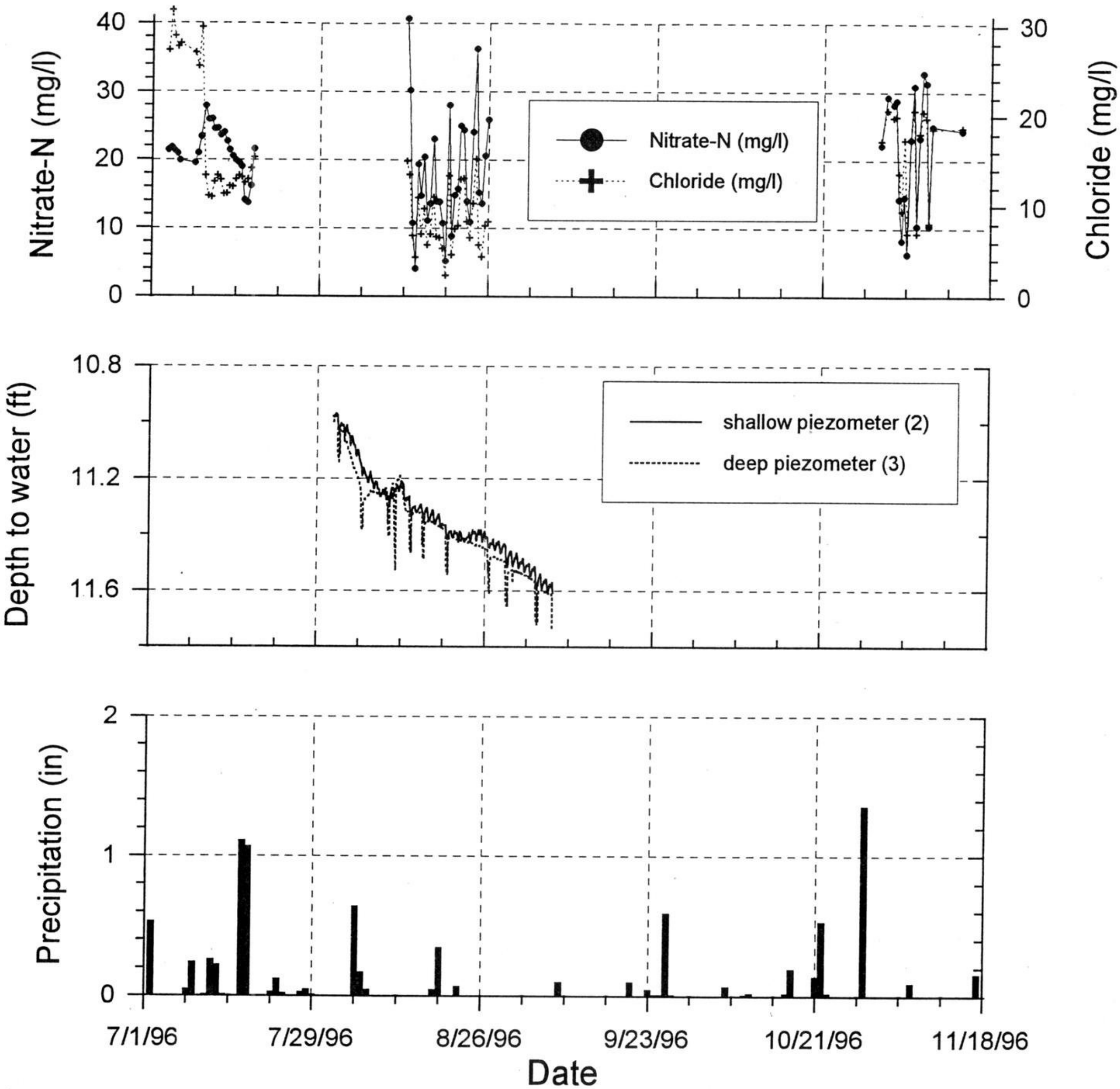

Figure 4. Water-quality, depth-to-groundwater, and precipitation data for 1996.

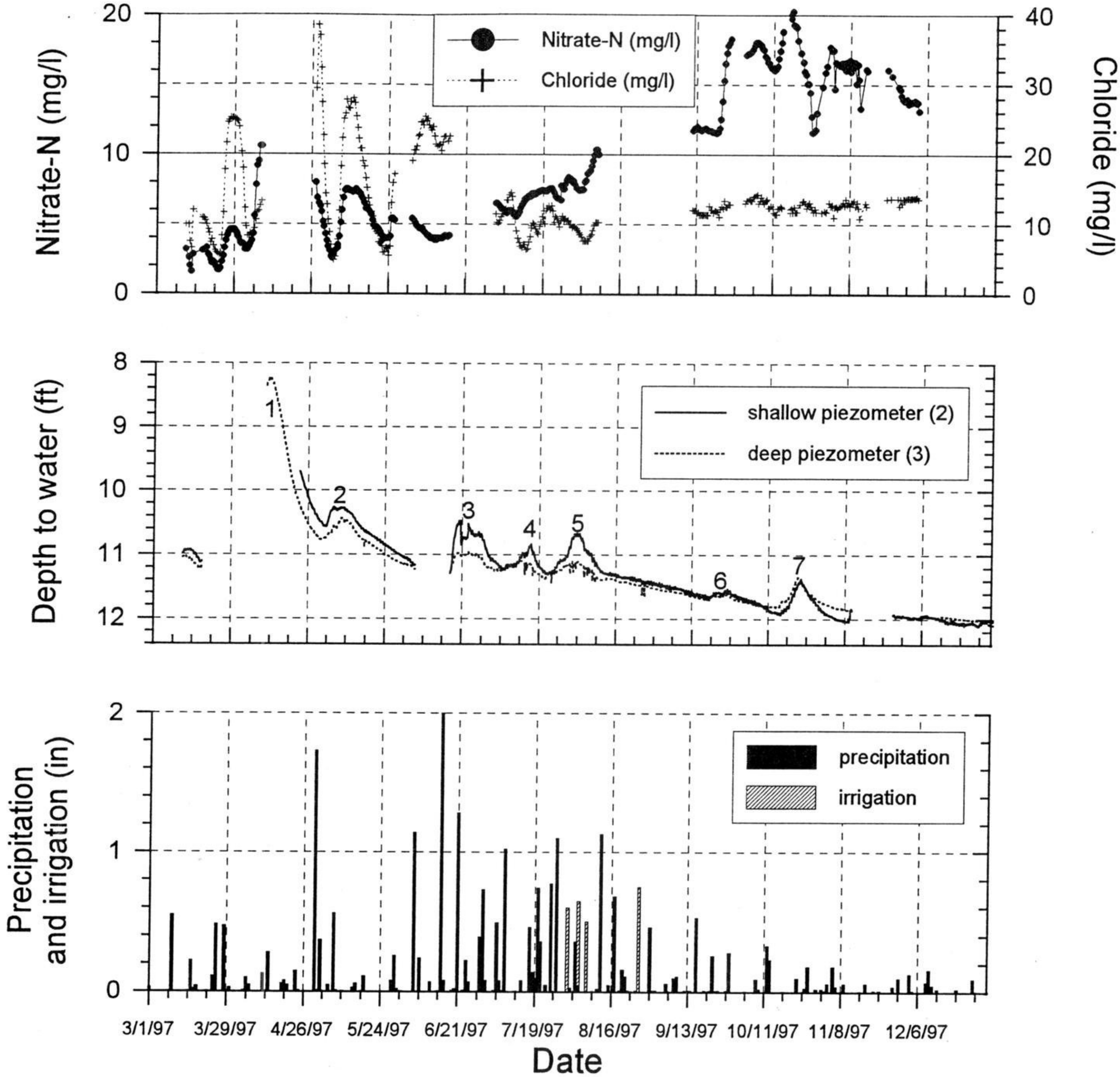

Figure 5. Water-quality, depth-to-groundwater, and precipitation data for 1997.

1996 Data

Equipment malfunctions and intrusion of wildlife into the equipment shed limited data recovery for 1996 (figure 4). The only monitoring period for which both water-level and water-quality data were collected is from late July to late August. The water-level data suggested that no recharge occurred over this time interval and the water-quality data were deemed to be unreliable; later data show smooth changes in water quality with time while the 1996 data show sharp changes in parameter values at 12-hour intervals.

1997 Data

Water-movement

Total precipitation for 1997 was 27.1 inches, and 2.45 inches of supplemental irrigation was applied to the research plots during July and August to meet crop needs (figure 5). Water levels fluctuated from 8.2 to 12.1 feet below the top of casing in the shallow piezometer and 9.7 to 12.1 feet below the top of casing in the deep piezometer. Throughout most of the year, hydraulic gradients were small and generally downward at the site. While there is an unfortunate gap in the water-level data from March 18 to April 10, existing data indicate that the major groundwater recharge event (1) occurred between March 18 and April 12, presumably in response to snow melt. After April 30, there are several smaller recharge events, however, groundwater levels generally decline throughout the year.

Recharge from May to August (events 2-5) appears directly linked to the precipitation record. There are subtle differences in groundwater-level response to precipitation throughout this time period. The magnitude and duration of response in the deep piezometer decrease and the lag-time between precipitation events and resulting water-level rise seems to increase once the crop cover has been established in the early summer.

The relationship between precipitation and water-level response is less clear in the fall of the year. Water levels rise in late September (event 6) and mid-October (event 7) after relatively small rain events. We assume that precipitation is moving more rapidly to the water table when plants have been harvested and thus losses to evapotranspiration are lessened.

Nitrate and Chloride Movement

A total of 186 lbs/A of nitrogen was applied during June and July to the field corn plots that occupied a majority of the site in 1997 (tables 1 and 2). Nitrate-N values from 332 water samples varied from 1.6 to 20.3 mg/l; chloride values varied from 4.9 to 39.7 mg/l (figure 5). Peak nitrate concentrations occurred in the fall of the year while chloride values peaked in spring. In order to examine the seasonal variations in water-quality data, we plotted graphs of the water quality, depth to groundwater, and precipitation for time intervals of approximately 100 days; these are presented in figures 6, 7, and 8 and described below. For each of these graphs, the major tick marks on the date axis are spaced every 7 days with minor tick marks every day (every other major tick mark is labeled.

<u>Spring 97:</u>

Figure 6 presents results from Spring 1997; for this time period we have also included soil temperature data. Data suggest that five separate pulses of both chloride and nitrate moved to the water table during the spring (indicated by dashed vertical lines in figure 6). As nitrogen was not applied until June 3, all of these pulses reflect transport of nitrogen applied during the 1996 growing season.

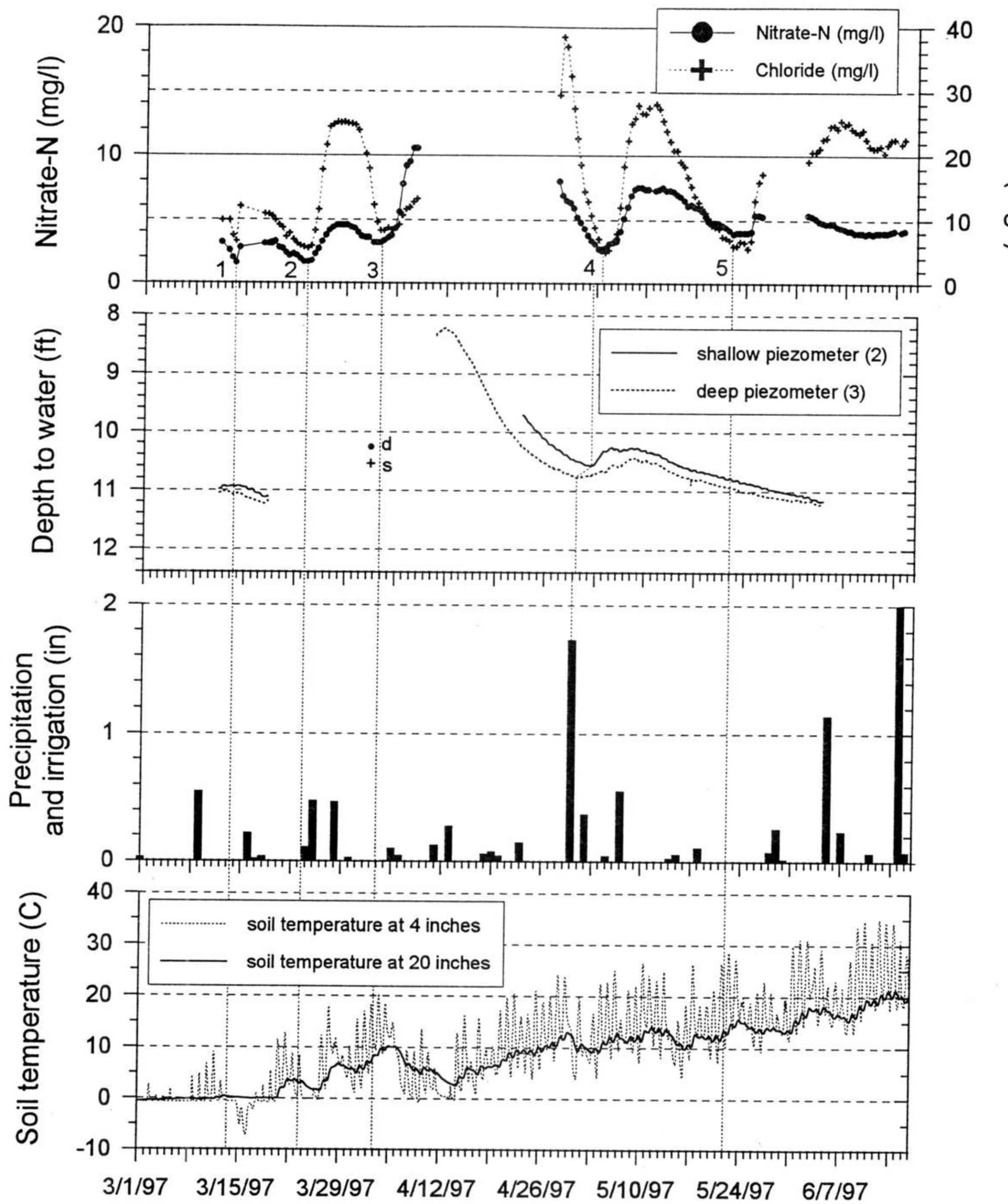

Figure 6. Water-quality, depth-to-groundwater, precipitation and soil temperature data for Spring 1997 (March 3 - June 17). Dotted vertical lines mark the beginning of five separate nitrate pulses that reach the water table during this time interval. Major ticks on the date axis are placed every 7 days (1 week) and every other major tick is labeled; minor ticks mark each day.

The first three pulses appear to be caused by snowmelt recharging the water table rather than specific precipitation events. During the week of March 8, frost had gone out of the upper portion of the soil profile as temperatures at 4 inches were consistently above 0° C while temperatures at 20 inches remained near 0° C. The water-quality data suggest minor pulses of both nitrate and chloride reach the water table as frost leaves the upper portions of the soil profile. A second and larger pulse of both nitrate and chloride reached the water table during the week of March 22 when soil temperatures were above 0° C to a depth of at least 20 inches.

Unfortunate gaps in the data limit the information available for the third nitrate pulse which began to reach the water table on April 3. It is unclear if this event was one large pulse or several smaller pulses, however, the nitrate values recorded on the rising-limb of the pulse were the highest observed that spring. Water-level data (including 2 field-measured water levels from April 1 shown as points in figure 6) suggest that the bulk of groundwater recharge occurred in early April as water-levels peaked on April 12 and then declined for several weeks.

The fourth nitrate pulse is the only one that appears to be linked with a specific precipitation event. The 1.7-inch rainfall on April 30 was followed by water level rises in both piezometers and the initiation of large chloride and nitrate pulses. It is unclear what drove the large chloride pulse and smaller nitrate pulse that began to reach the water table on May 22 as there are no large precipitation events in the previous week and water-levels declined over this time interval.

<u>Summer 1997:</u>

Figure 7 presents results from Summer 1997. Nitrate and chloride concentrations show the least variability of the year during the growing season. Interestingly the two parameters, both of

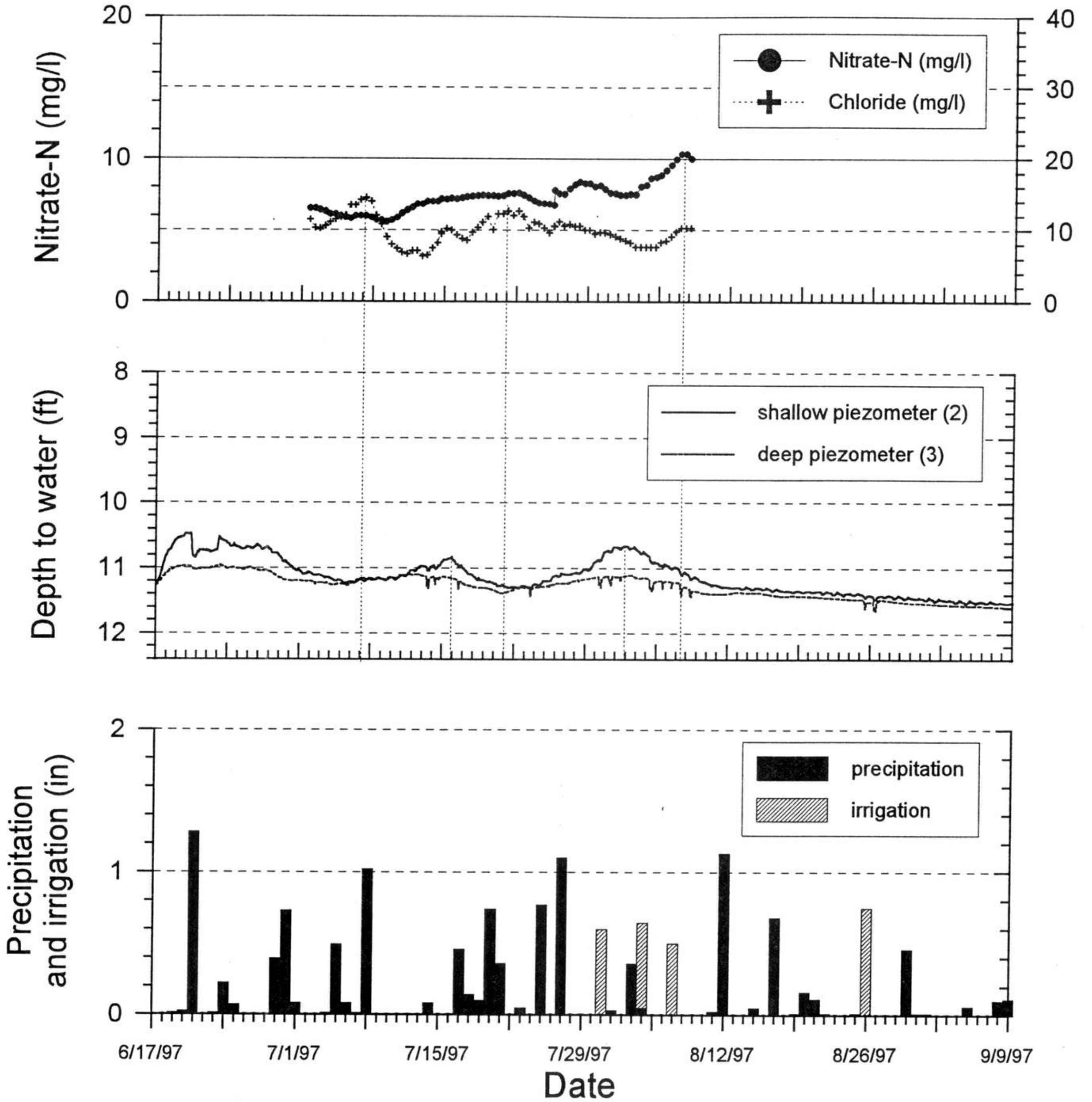

Figure 7. Water-quality, depth-to-groundwater, precipitation and irrigation data for Summer 1997 (June 17 - Septemebr 9). Dotted vertical lines mark peaks in water levels and chloride concentrations. Major ticks on the date axis are placed every 7 days (1 week) and every other major tick is labeled; minor ticks mark each day.

which are considered conservative anions, exhibit differing variations in concentration. The nitrate concentrations decrease until July 9 and then generally increase over the growing season with two small pulses in late July and early August. Variations in nitrate are difficult to correlate with specific recharge events and may be somewhat controlled by variations in uptake by the crop cover.

Chloride concentrations show more variability with several distinct pulses arriving at the water table during this time period. Three of the chloride pulses (shown as dashed vertical lines in figure 7) appear to be linked to groundwater recharge events as the peak chloride concentrations are recorded approximately 5 to 5.5 days after peak water-level readings in piezometer 2.

Fall 1997:

Data from 9/10 to 12/31/97 are presented in figure 8. Nitrate-N concentrations were the highest of the year (12 to 21 mg/l) and values were consistently above the drinking water standard of 10 mg/l. Chloride concentrations were generally low and showed little variability during this time period.

Nitrate concentrations started to increase on September 21 and there are four distinct nitrate pulses during this time interval (shown as dashed vertical lines in figure 8). The first of the pulses (starting September 21) correlates with a minor rise in water levels due to the 0.6-inch rain event 5 days previously (9/16/07). The remaining three pulses are not strongly correlated with groundwater recharge events. Two small pulses began to arrive to the water table on September 30 and October 11, both pulses follow small rainfall events that are not reflected in the water-level record. Indeed, large rainfall events appear to correlate with drops in nitrate concentration. If the rain of 10/12 and 10/13 is what caused the water levels to begin increasing on 10/16, this appears

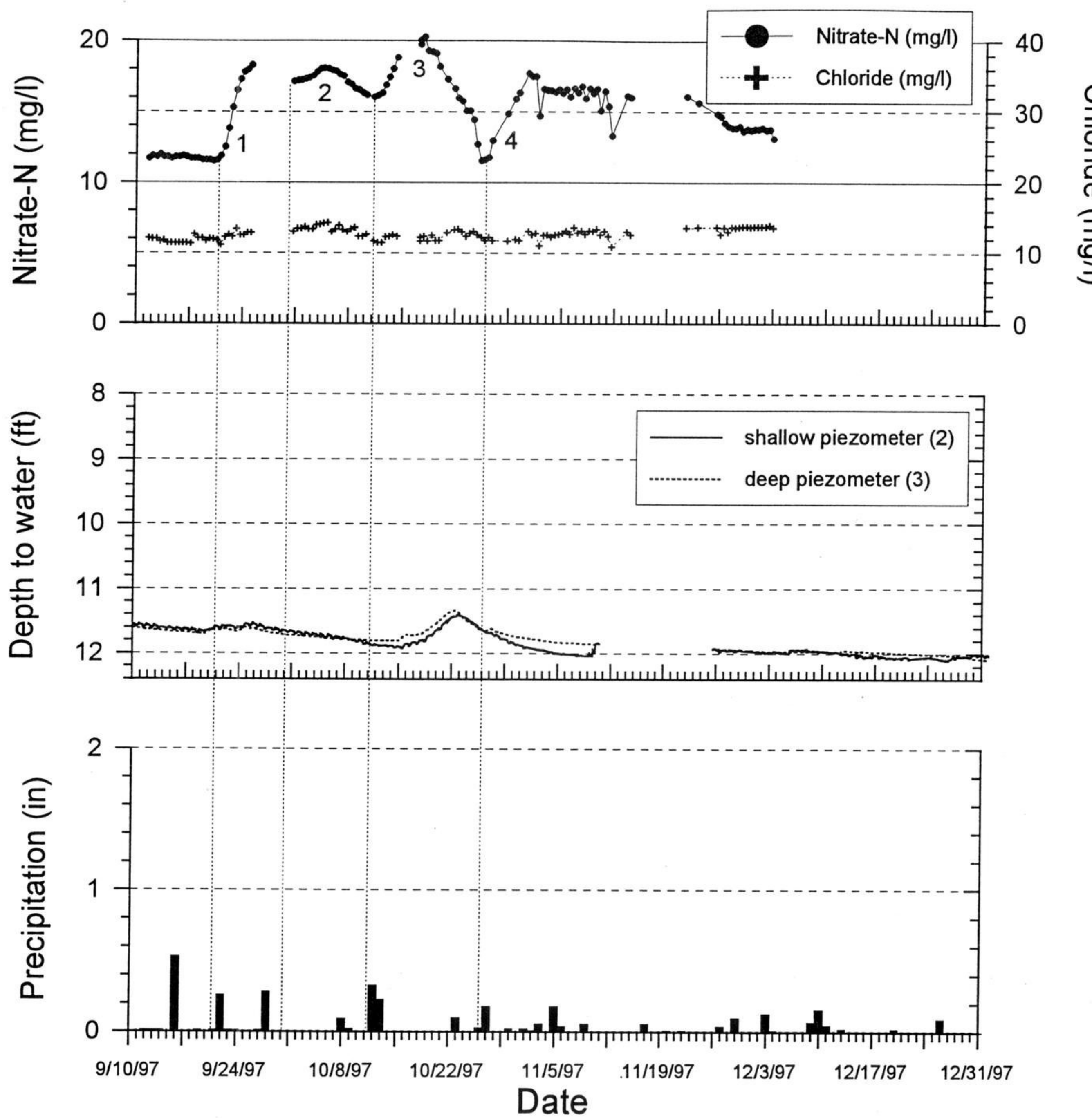

Figure 8. Water-quality, depth-to-groundwater, and precipitation data for Fall 1997 (September 10 - December 31). Dotted vertical lines mark the beginning of four separate nitrate pulses that reach the water table during this time interval. Major ticks on the date axis are placed every 7 days (1 week) and every other major tick is labeled; minor ticks mark each day.

to cause a drop in nitrate concentrations as the lowest nitrate values are recorded on 10/26. The fourth nitrate pulse (beginning 10/26) occurred during a period of generally low rainfall and declining water levels.

In general, it appears that nitrate movement in the fall may be more correlated with crop activity than with precipitation or recharge events. The 110-day corn planted on June 3 would have reached it's maturation date on 9/28/97 and begun to die back. As the corn died back evapotranspiration would have dropped off and active uptake of nutrients would have ceased allowing gravity drainage of existing soil moisture and nitrate from the deep root zone.

1998 Data

Water level data were recorded from 1/1 to 6/18 1998 while water-quality sampling was initiated in the spring after air temperatures had warmed enough so that the sampling line would not freeze (figure 9). Water levels indicate that there was a minor recharge event in late February and that the major spring recharge event occurred in late March to early April. Samples collected from 4/1 to 4/14/98 captured a nitrate pulse that was carried to the water table with the recharging water.

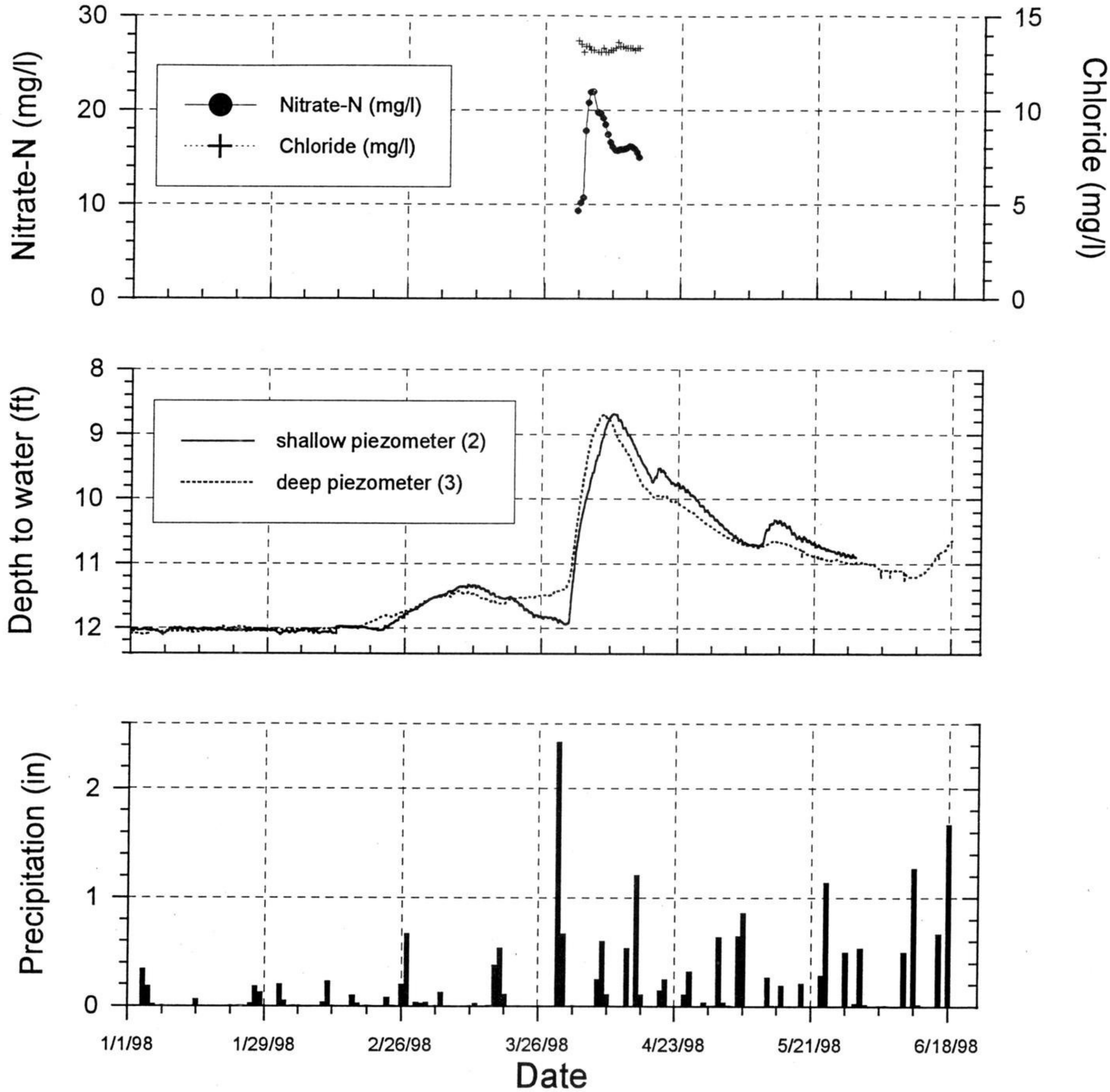

Figure 9. Water-quality, depth-to-groundwater, and precipitation data for 1998 (January 1 - June 18). Major ticks on the date axis are placed every 28 days (4 weeks); minor ticks mark each week.

IMPLICATIONS FOR MONITORING

Management of nutrients applied to agricultural lands is a growing concern in Wisconsin as recent sampling programs have revealed that a significant number of rural wells exceeds the state's drinking-water standard of 10 mg/l of nitrate-N (Kraft, 1994). Concern about nutrient management, especially management of animal wastes, is likely to continue as the number of farms with more than 1000 animal units is currently increasing. We need to understand the seasonal variability of nitrate movement to the water table in order to 1) design effective monitoring systems and 2) develop effective nutrient management plans. The objectives of this project were 1) to determine the temporal variability in nitrate concentrations in shallow, sandy aquifers, 2) to define the relationship between recharge and groundwater nitrate concentrations, and 3) to develop recommendations concerning monitoring frequency for such aquifers.

Water-quality and water-level data from the 1997 and 1998 growing seasons suggest that variations in nitrate concentrations at the water table are a function of both 1) groundwater recharge events and 2) crop uptake and that these factors vary seasonally. The standard practice of quarterly groundwater sampling (4 camples/year) is inadequate in shallow sandy aquifers as nitrate and chloride fluctuate much more rapidly. Indeed many projects designed to assess the use of agricultural pest management practices on groundwater quality consider "frequent" menitoring to be monthly. It is clear from this study that neighter quarterly nor monthly sampling would fully characterize the nitrate loading to the water table in this setting. Effective monitoring strategies need to be designed with the following considerations.

•In the spring, pulses of nitrate move to the water-table with recharging snowmelt. These pulses are not linked to specific precipitation events but rather the timing of the frost leaving the soil profile. Elevated nitrate values are observed on the rising-limb of the hydrograph. Nitrate concentrations increase rapidly; the 1998 data indicate a change of 10 mg/l in a 24-hour period. This rapid rise in nitrate concentrations suggests that frequent sampling is necessary to capture the loading of nitrate due to spring recharge. The timing of springtime monitoring efforts needs to be based on soil-temperature data rather than either precipitation or water-level data.

•Once the crop cover has been established, nitrate appears to be less mobile, concentrations are relatively stable, and variations in concentration are difficult to correlate with specific precipitation events. This behavior contrasts with that of chloride, another conservative anion. Pulses of chloride arrive at the water-table approximately 5 to 5.5 days after peak water levels are recorded in the shallow piezometers. The reduced mobility of nitrate during the summer months is assumed to be due to uptake of nitrogen by the actively growing crop cover. Because of its extremely conservative nature, chloride appears to be a better indicator of the impacts of rainfall events on the saturated zone, particularly during the active evapotranspiration period. Reliable nitrate data are only available for the summer of 1997. The largest rainfall event during this period was 1.28 inches. While nitrate concentrations did not correlate with specific precipitation events in that year, it is possible that very large rainstorms (>1.3 in) could move nitrate to the water table.

•From the late summer (Aug 15) on, nitrate movement appears to be correlated with crop activity rather than with precipitation or recharge events. Once crops mature, evapotranspiration decreases and active uptake of nutrients ceases thus allowing gravity drainage of existing soil moisture and nitrate from the deep root zone. The nitrate data from 1997 suggest that a large percentage of the nitrate applied to fields during the growing season moves to the water table in the fall of the year as the highest nitrate concentrations were observed in fall. The relation between precipitation and nitrate concentrations in not straightforward. In late September 1997, rising water levels correlate with increasing nitrate concentrations, while in late October 1997, a rise in water levels appears to correlate with a low in nitrate concentrations. Given this behavior, it is not clear if fall monitoring needs to be linked with specific recharge events.

Recommendations

In summary, nitrate movement in sandy aquifers with a shallow water table seems controlled both by groundwater recharge events and crop activity. The standard practice of quarterly groundwater sampling is inadequate to characterize nitrate loading to the water table. The following recommendations for groundwater monitoring programs are based on the data from the Arena site and should be applicable in similar hydrogeologic settings. Effective monitoring schemes will need to incorporate data on soil-temperature, groundwater levels, daily precipitation, and crop maturation dates. Figure 10 presents the nitrate data from the Arena site with different symbols illustrating differing sampling frequencies.

•Springtime monitoring should be initiated as the frost is going out of the soil profile (based on soil temperature data). Both the 1997 and the 1998 data suggest that weekly sampling would be insufficient to capture the variability of nitrate loading during the primary spring recharge event (figure 10). Sampling should be frequent, approximately daily or every other day, during the primary recharge event (as determined by groundwater level data) and then perhaps sampling frequency could decrease to weekly with little loss of information.

•Once crop cover is well-established, sampling frequency can decrease to biweekly of monthly (figure 10). It may be prudent to link sampling events with large precipitation events.

•Data from fall 1997 suggests that sampling frequency should increase to weekly as the crop maturation date approaches.

•We have no recommendations for wintertime sampling frequencies as no water-quality data were collected over the winter months. It is difficult to keep automatic samplers from freezing during this time period. Monthly samples taken driectly from the well might suffice for these months.

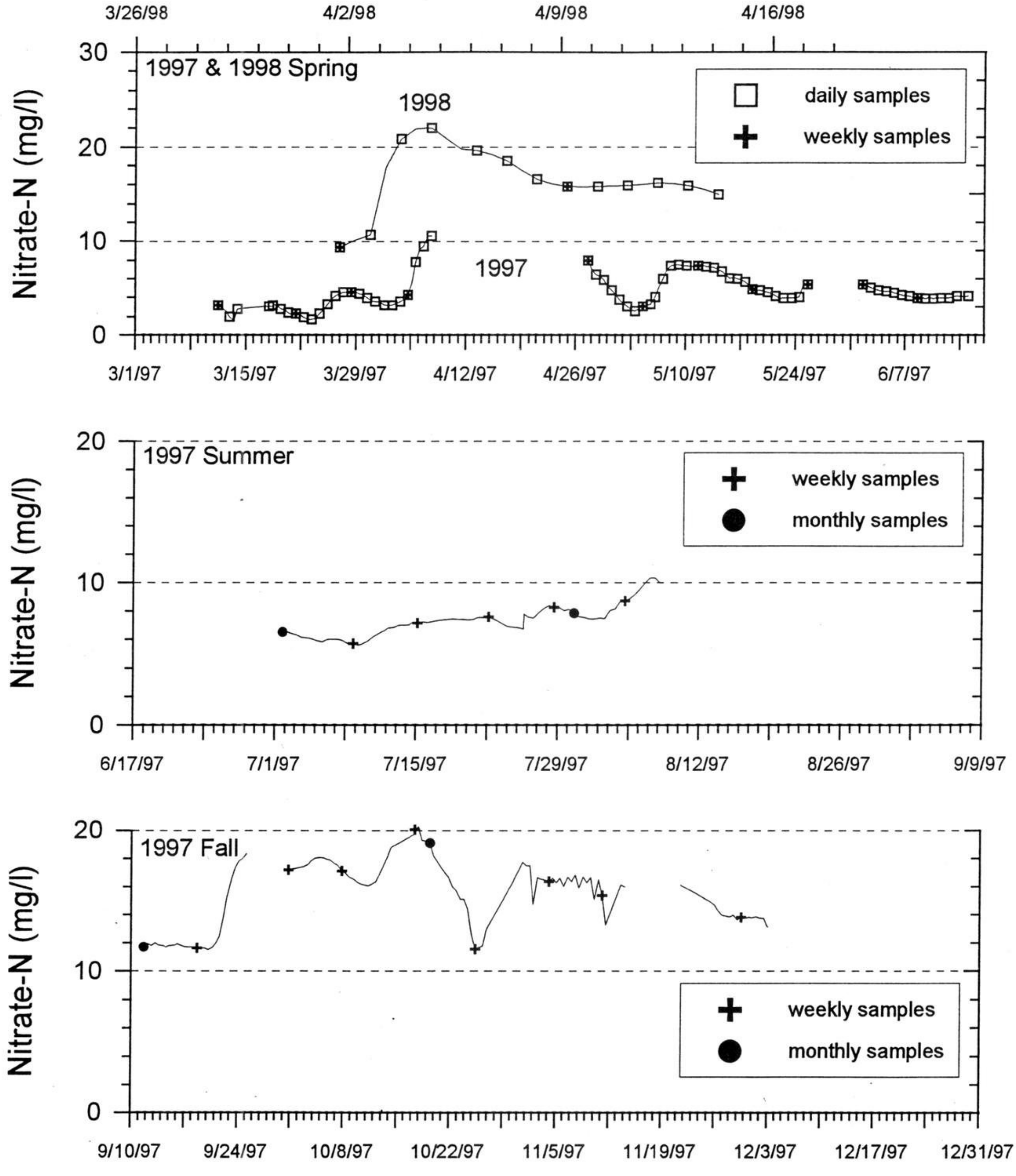

Figure 10. Plots of the nitrate-N data illustrating differing sampling frequencies. The solid line in each graph shows the variability recorded with samples collected every 12 hours. The different symbols illustrate daily (open square), weekly (plus sign), and monthly (closed dot) sampling frequencies.

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