Impact of Alternative Citrus Management Practices on Groundwater Nitrate in the Central Florida Ridge
I. Field Investigation

S. T. Lamb, W. D. Graham, C. B. Harrison, A. K. Alva

Abstract. *A research project was conducted to evaluate the impact of alternative citrus nitrogen and water management practices on groundwater nitrate concentrations beneath the vulnerable sandy soils in the ridge citrus region of Central Florida. Fifteen months of baseline data indicated that groundwater nitrate-nitrogen concentrations were above the Environmental Protection Agency's Maximum Contaminant Level (MCL) beneath mature groves on the Central Florida Ridge. Data from beneath a flatwoods grove off the ridge showed groundwater nitrate-nitrogen levels well below the MCL, and data from beneath a native vegetation site on the Central Florida ridge showed virtually no detectable nitrate-nitrogen in groundwater. After the baseline monitoring period the following site-specific best management practices (BMPs) were implemented: (1) application of a combination of slow release and dry soluble fertilizer at a rate of 180 kg N/ha/yr split into three applications; (2) application of 18 doses of liquid fertilizer at a rate of 180 kg N/ha/yr applied through a fertigation system; (3) application of 18 doses of liquid fertilizer at a rate of 168 kg N/ha/yr applied through a fertigation system; (4) application of a combination of 18 doses of liquid fertilizer at a rate of 78 N kg/ha/yr through a fertigation system and three applications of foliar spray fertilizer at a rate of 64 kg N/ha/yr (total 142 kg N/ha/yr); and (5) use of irrigation scheduling based on tensiometer measurements to minimize excess leaching. Analysis of 52 months of post-BMP monitoring data indicated that all of these BMPs produced statistically significant downward trends in nitrate-nitrogen concentration, and all have the potential to meet the EPA MCL for groundwater. The average downward trends ranged from −0.4 to −4.6 mg NO_3-N/L-yr, and were greatest for the fertigation/foliar spray BMP, which represented the largest reduction in total N applied.*

Keywords. *Citrus, Best management practices, Groundwater, Quality monitoring, Nitrate-nitrogen.*

A recent National Pesticide Survey conducted by the U.S. Environmental Protection Agency (USEPA, 1990) found widespread nitrate-nitrogen contamination of drinking water wells, with approximately 52% of the urban drinking water wells and 57% of the rural drinking water wells containing nitrate-nitrogen concentrations above background levels. Approximately 1.2% and 2.4% of urban and rural drinking wells, respectively, were found to contain nitrate-nitrogen concentrations above the Maximum Contaminant Level (MCL) of 10 mg/L. The survey revealed a consistent pattern of drinking water well contamination in areas with higher fertilizer sales and higher crop values, indicating that agricultural practices may be important contributors to the nitrate-nitrogen problem.

In predominantly agricultural regions of Florida, the frequency of drinking water wells contaminated by nitrate-nitrogen exceeds the national frequency found in the EPA survey (Riotte and Graham, 1994; Garret et al., 1997). Of 3,949 drinking water wells analyzed for nitrate-nitrogen by the Florida Department of Agriculture and Consumer Services (FDACS) and the Florida Department of Environmental Protection (FDEP), 2,483 (63%) contained detectable nitrate-nitrogen and 584 (15%) contained nitrate-nitrogen above the EPA MCL. Of the 584 wells statewide that exceeded the MCL, 519 were located in the Central Florida Ridge citrus growing region, encompassed primarily by Lake, Polk, and Highlands Counties.

As a result of the Florida groundwater quality surveys, FDACS formed a multi-agency Nitrate Study Committee in October 1992. The purpose of this committee was to develop a long-term project to evaluate the impacts of alternative citrus nutrient and water management practices on the groundwater beneath commercial citrus groves on the Central Florida Ridge. Specific objectives of this research project were to: (1) generate baseline groundwater nitrate data from several commercial citrus groves in the Central Florida Ridge region in order to relate current groundwater nitrate trends to existing and historic management practices; (2) develop recommendations for alternative nutrient and water management practices for each cooperator site intended to reduce off-site groundwater nitrate impacts associated with citrus production; and (3) assess the impacts of alternative management practices on groundwater nitrate-nitrogen. This article summarizes baseline hydrologic and groundwater nitrate data collected during the September 1993 through January 1995 time period, and assesses the impact of alternative management practices implemented

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The authors are **Scott T. Lamb**, Engineer (presently with St. Johns River Management District, Melbourne, Fla.), **Wendy D. Graham**, ***ASAE Member Engineer***, Professor, and **Catherine B. Harrison**, Graduate Student, Department of Agricultural and Biological Engineering, University of Florida, Gainesville, Florida; and **Ashok K. Alva**, Associate Professor, University of Florida Citrus Research and Education Center, Lake Alfred, Florida. **Corresponding author:** Dr. Wendy Graham, University of Florida, Agricultural and Biological Engineering Dept., Rogers Hall, PO Box 110570, Gainesville, FL 32611-0570, voice: (352) 392-9113, fax: (352) 392-4092, e-mail: graham@agen.ufl.edu.

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in January 1995 on groundwater nitrate over the January 1995 through April 1999 time period. Assessment of the impact of alternative management practices on leaf nutrient concentrations, fruit quality, and fruit yield response is reported by Graham and Alva (1998) and Alva et al. (1998).

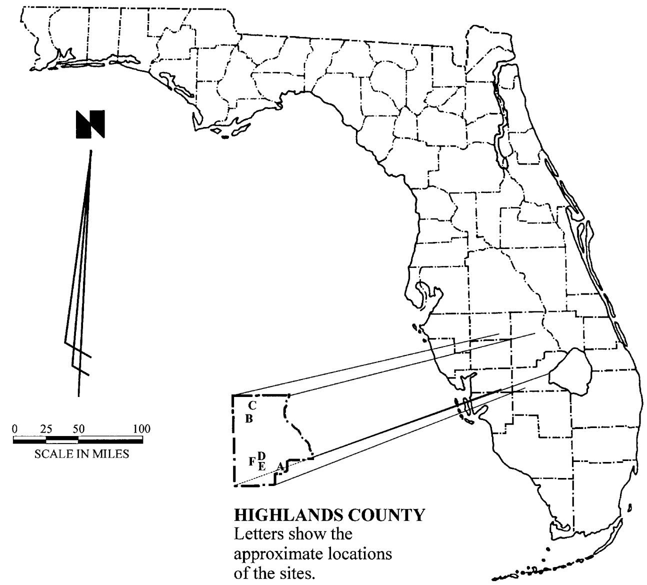


Figure 1–General site location map.

Study Area Description

The Central Florida Ridge consists of an extensive series of ridges, subparallel to the present Atlantic Coast, that were probably formed as linear coastal features. Parts of these ridges, with elevations greater than 30 m above Mean Sea Level (MSL), have never been submerged during the recent geological past of the Wimcomico sea level, and are composed of well-sorted sands with very little organic content. The easterly most ridge is the Lake Wales Ridge. This ridge is significant because of its high elevation and deep sand and, although only a few kilometers wide, it is over 160 km long. The Lake Wales Ridge is a region of mature Karst topography, as evidenced by the Intraridge Valley. This axial valley with its underlying soluble limestone is denoted by a long line of lakes which, when combined with the lakes through the Trail Ridge area, comprises the longest smooth line of associated lakes in the United States (Brooks, 1982; White, 1970).

Sedimentary rocks exposed on the Lake Wales Ridge range in age from Miocene to Recent. Depth of the overlying Pleistocene sands, which degrade into sands and clay, ranges up to 75 m below MSL. Marine deposits of the Hawthorn Formation underlie the region and rest on Suwannee Limestone in the Oligocene Series. The Suwannee Limestone represents the top of the Floridan aquifer system (Bishop, 1956; Kohout and Meyer, 1959).

Municipal and irrigation wells in the region are typically cased to an average depth of 150 m and withdraw from the Floridan aquifer. Of primary concern for this study is the quality of water in the overlying surficial aquifer, which encompasses the fine, well-sorted sands on the Lake Wales Ridge. This surficial system provides drinking water for many individual homeowners. The source of this fresh water is local rainfall (SWFWMD, 1990). This rainfall infiltrates through the sand, apparently carrying nitrates, which have caused the groundwater nitrate problem.

Twenty-one citrus groves in the Highlands county portion of the Lake Wales Ridge were nominated as potential sites for this study (see fig. 1). Of the original 21 sites, six were chosen based on several criteria including: (1) isolation from upstream nitrate sources; (2) depth to groundwater; (3) soil type; (4) nutrient and water management practices; and (5) horticultural characteristics representative of the region. Table 1

Table 1. Cooperator site characteristics

Characteristic	Site A	Site B	Site C	Site D	Site E	Site F
Scion	Hamlin	Valencia	Valencia	Valencia	Valencia	Native vegetation
Rootstock	Sweet orange	Rough lemon	Volkamer lemon	Rough lemon	Rough lemon	
Year planted	1965	1963	1990	1959	1959	
Tree density	286 trees/ha	212 trees/ha	445 trees/ha	286 trees/ha	286 trees/ha	
Monitored area	14 ha	20 ha	15 ha	32 ha	32 ha	
Soil type	Pineda sand (flatwoods)*	Astatula, Duette, and Orsino sand (ridge sand)	Astatula sand (ridge sand)	Astatula and Paola sand (ridge sand)	Astatula and Paola Sand (ridge sand)	St. Lucie, Duette, and Basinger sand (ridge sand)
Irrigation method	Drip irrigation	Micro-irrigation	Micro-irrigation	Micro-irrigation	Micro-irrigation	---
Ave pre-BMP N use (5 years)	140 kg/ha dry soluble (2 applications)	285-203 kg/ha† dry soluble (3 applications)	120-210 kg/ha‡ dry/fertigation (1-3 applications)	283-194 kg/ha† dry soluble (3 applications)	283-194 kg/ha† dry soluble (3 applications)	---
Recommended BMP N use	Continue previous practice	142 kg/ha fertigation§/ foliar spray‖	168 kg/ha fertigation§	180 kg/ha dry soluble/ slow release#	180 kg/ha fertigation§	---

* Drainage ditches are used at this site to control groundwater levels.
† N use systematically reduced over the five-year period.
‡ N use systematically accelerated from the 1990 planting date.
§ 18 fertigations applications in January-May, September-October.
‖ 3 foliar sprays in March, September, December.
January (45 kg dry, 45 kg slow release), April (45 kg dry), September (45 kg dry).

summarizes the hydrogeologic and horticultural characteristics of the six selected sites. Sites B through E are commercial citrus groves located on the Central Florida Ridge. For comparison purposes, Site A is a commercial citrus grove located on a flatwoods soil off the Ridge, and Site F is a native vegetation site located on the Ridge at Archbold Biological Station near Lake Placid, Florida.

Site Instrumentation and Monitoring

In summer 1993, each of the six sites was instrumented in order to monitor hydrologic conditions and groundwater nitrate concentrations. Five piezometers were installed around the perimeter of each site. Data from these piezometers are used to determine the depth to the water table, horizontal flow direction, and hydraulic gradient. The piezometers are constructed of 5 cm PVC piping with 0.025 cm slotted screen, installed over the top 3.0 to 4.6 m of the aquifer. Fifteen multi-level samplers (MLSs) were installed at Sites A, B, and C; 16 and 14 MLSs were installed at Sites D and E, respectively; and six MLSs were installed at Site F. The purpose of the MLSs is to measure the distribution of nitrates with depth in the groundwater, and to allow accurate detection of changes in groundwater nitrates at the top of the surficial aquifer due to changes in on-site management practices (Graham and Downey, 1992). The MLSs were designed and installed so that the top 6 m of the surficial aquifer was monitored using 10 sampling ports spaced at 0.6 m intervals. The MLSs were installed along two or three transects within each site, and the uppermost port of each MLS was positioned at the highest expected water table elevation. The MLSs were drilled between trees, approximately 60 m apart along the tree rows. Weather stations installed at Sites A and F recorded rainfall, pan evaporation, and daily maximum and minimum temperatures. Rainfall was also recorded at Sites B, C, D, and E.

Each piezometer water level was measured monthly and groundwater samples were taken every six months from these wells to provide background depth-integrated nitrate-nitrogen concentrations. Each MLS was sampled every two weeks to provide information on the spatial and temporal distribution of nitrate-nitrogen in groundwater beneath each grove. Sampling, quality assurance and quality control procedures were summarized in a Quality Assurance Project Plan on file with the Florida Department of Environmental Protection Quality Assurance Section (QAPP No. 930206N).

Data Analysis Methods

The concentration of nitrate-nitrogen at each depth in the aquifer for every sampling date was averaged over all multilevel samplers for each site. Average values for each depth were analyzed to determine both the pre-BMP (baseline) and the post-BMP mean and variance for each data series. The null hypothesis that the pre-BMP mean was equal to the post-BMP mean for each data series was tested against the alternative hypothesis that the post-BMP mean was less than the pre-BMP mean using a one-sided t-Test (Walpole and Myers, 1978). The decision to reject the null hypothesis was made at the 95% confidence (5% significance) level. To check for the existence of trends in the groundwater nitrate time series, graphical and non-parametric statistical methods were used. Berryman et al. (1988) provides a comprehensive review of water quality trend-detection methods. A brief discussion of these methods follows.

Graphical methods facilitate trend analyses by qualitative or quantitative interpretation of a graph. Commonly used graphical methods include plots of data series versus time, histograms, seasonal box and whisker plots, plots of double mass function versus time, and plots of cumulative sum versus time. The double-mass function graph plots accumulated sums of the water quality variable (ΣX_j, j = 1, . . . , t) on the ordinate, and time t (expressed as number of days since the first measured observation) on the abscissa (Cluis, 1988). These plots are useful for qualitatively identifying the presence and amplitude of possible trends in the series. The cumulative sum function graph plots accumulated sums of the water quality variable minus the accumulated mean, ($\Sigma X_j - j \cdot \overline{X}$) on the ordinate, and time (t) since the first measured observations on the abscissa (Cluis, 1988). These plots can provide additional visual evidence of a trend, and help to evaluate whether a monotonic or stepwise trend is more appropriate for the data series.

Graphical analysis typically requires the series to be normally distributed with homogeneous variance over time (Weiss and Wilson, 1953). Furthermore, for sample sizes less than 50, plotting techniques may be insufficient (Montgomery and Reckhow, 1984). In this study, plots of data series versus time, double-mass plots, and cumulative sum plots were produced to aid in preliminary data analysis. These plots were not used as a final test for the presence of a trend, because of the limitations of graphical methods.

Statistical tests differ from graphical tests in the way trends are detected. Using statistical tests an objective and quantitative decision rule is applied to the data. The rule is to consider a trend as significant when its magnitude is large compared to the variance of the process, so that the probability of its occurrence by chance is minimal (Berryman et al., 1988). An assumption central to most parametric statistical tests, such as linear regression, is that the data have a normal distribution. Parametric tests also require observations for which the error terms are independent and have constant variances. Table 2, taken from Berryman et al. (1988), summarizes the characteristics of water quality time series that limit the use of commonly used methods for trend detection.

Table 2. Commonly used methods for trend detection and the characteristics of water quality data that limit their use

	Data Characteristics Limiting the Use of the Statistical Method			
Trend Selection Methods	Dependence of Error Terms	Non-normal Distribution of Error Terms	Non-constant Variance of Error Terms	Obs. Below Detection Limit
Graphic methods	Yes	Yes	Yes	No
Parametric tests	Yes	Yes	Yes	Yes
Traditional non-parametric tests	Yes	No	No	No
Modern non-parametric tests	No	No	No	No

Traditional non-parametric tests, in general, are robust with respect to non-normal error distributions with heterogeneous variances. Other advantages of non-parametric tests over parametric tests are that truncated observations (i.e., below the detection limits) can be included in the computation of the test statistic, and the tests are not grossly affected by outliers and missing data (Conover, 1971; Lettenmaier, 1976; Marascuilo and McSweeney, 1977; Hirsch et al., 1982). However, use of traditional non-parametric tests to detect trends in water quality data is complicated by the fact that water quality time series often exhibit mutually dependent observations (Berryman et al., 1988). In recent years, however, non-parametric procedures have been adapted to account for dependence due to cyclic variations (Hirsch et al., 1982; Van Belle and Hughes, 1984) and persistence (Lettenmaier, 1976; Hirsch and Slack, 1984; Lettenmaier, 1988). Table 3, taken from Berryman et al. (1988), presents tests adapted by various investigators to account for dependence in water quality data series, and the minimum number of data observations required to apply each test. Details on the theory and mechanics of these tests can be found in the cited references. In this study the non-parametric statistical tests summarized in table 3 were performed on the groundwater nitrate-nitrogen data series. The software package "Detect" (Cluis, 1988) was used to conduct the graphical and non-parametric statistical analyses. The decision to reject the null hypothesis that there was no time series trend was made at the 95% confidence (5% significance) level.

Results and Discussion

The monthly rainfall totals, annual rainfall totals and the study period average rainfall recorded at Sites A through F are shown in figure 2. Note that while rainfall records were available for the complete study period at Sites A and F, rainfall measurement did not begin until September 1995 at Sites B, C, D, and E. Figure 2 shows that, at all sites, average rainfall over the study period was close to the regional long-term annual average of 1320 mm. However, during 1996 all sites received substantially less than the annual average rainfall. Also, during February and March 1998 the region received much higher than normal rainfall due to the effects of El Nino.

Figure 3 shows time series of average piezometric head elevation above mean sea level for each site over the study period. Figure 3 shows that at Site A (the drained flatwoods site) groundwater levels were managed so that the water table stayed below approximately 8 m above mean sea level. In general, Sites B through F show the characteristic seasonal pattern for the area: highest groundwater levels in September and October of each year (following the summer rainy season) and lowest groundwater levels in May of each year (following the spring dry season). However, departures from this typical behavior were recorded in 1998 due to the extremely wet spring season attributed to El Nino.

Histograms of the nitrate-nitrogen concentrations measured at each site over the baseline time period are shown in figure 4. The data in figure 4 show that baseline groundwater nitrate-nitrogen concentrations beneath the native vegetation site (Site F) were generally below detection limits. The average nitrate-nitrogen concentration over the top 6 m of the surficial aquifer beneath Site F was 0.01 mg/L. Figure 4 shows that most of the baseline groundwater nitrate-nitrogen concentrations beneath the Flatwoods grove off the ridge (Site A) were also below detection limits, with a small number showing elevated nitrate-nitrogen. The average baseline groundwater nitrate-nitrogen concentration at Site A was 0.99 mg/L. These findings are consistent with previous studies of groundwater nitrate-nitrogen beneath citrus and vegetables grown on Florida flatwoods soils (McNeal et al., 1995). Figure 4 shows that the majority of the baseline groundwater samples taken from beneath mature ridge citrus groves (Sites B, D, and E) exceeded the EPA MCL for nitrate-nitrogen. Site B showed the most heavily impacted groundwater with an average nitrate-nitrogen concentration of 27.9 mg/L. Site D and Site E had average groundwater nitrate-nitrogen concentrations just above the MCL during the baseline period, at 11.0 mg/L and 10.1 mg/L, respectively. Figure 4 shows that groundwater nitrate-nitrogen concentrations at Site C were well above background, with an average value equal to 6.5 mg/L over the baseline period. It should be noted that Site C was a native vegetation site prior to planting to citrus in 1990.

The baseline monitoring data was used to guide the selection of alternative management practices for each site. Table 1 includes a summary of the nitrogen management practices recommended for each site, which were implemented by the grower cooperators in January 1995. Since preliminary findings at Site A showed no significant impact of citrus production on groundwater, no change in nitrogen management practice was recommended for this site. At the remaining sites both a reduction in total nitrogen applied, and an increase in the number of applications per year, were recommended. At Site B, the most heavily impacted site, total nitrogen was cut back to 142 kg/ha: 57% of the average nitrogen applied over the previous 5 years, and 68% of the average nitrogen applied over the previous two years. At Sites D and E, total nitrogen was cut back to 180 kg/ha: 74% of the average nitrogen applied over the previous five years, and 90% of the average nitrogen applied over the previous two years. At Site C, the young grove, 168 kg/ha nitrogen was recommended. This rate is equivalent to the average nitrogen applied over the previous five years, with no annual increase recommended for the developing trees. It was also recommended that no nitrogen fertilizer be applied at any site during the June through August summer rainy season, in order to minimize the chance of nitrogen leaching to groundwater.

Table 3. Modern non-parametric tests for monotonic trends in water quality time series

Series Characteristics				
Seasonality	Persistence	Test	Reference	Minimum No. Obs.
No	No	Kendall	Kendall (1975)	9
Yes	No	Kendall/Seasonality	Hirsch et al. (1982)	24
No	Yes	Spearman/Lettenmaier	Lettenmaier (1976)	20
Yes	Yes	Hirsch/Slack	Hirsch and Slack (1984)	120

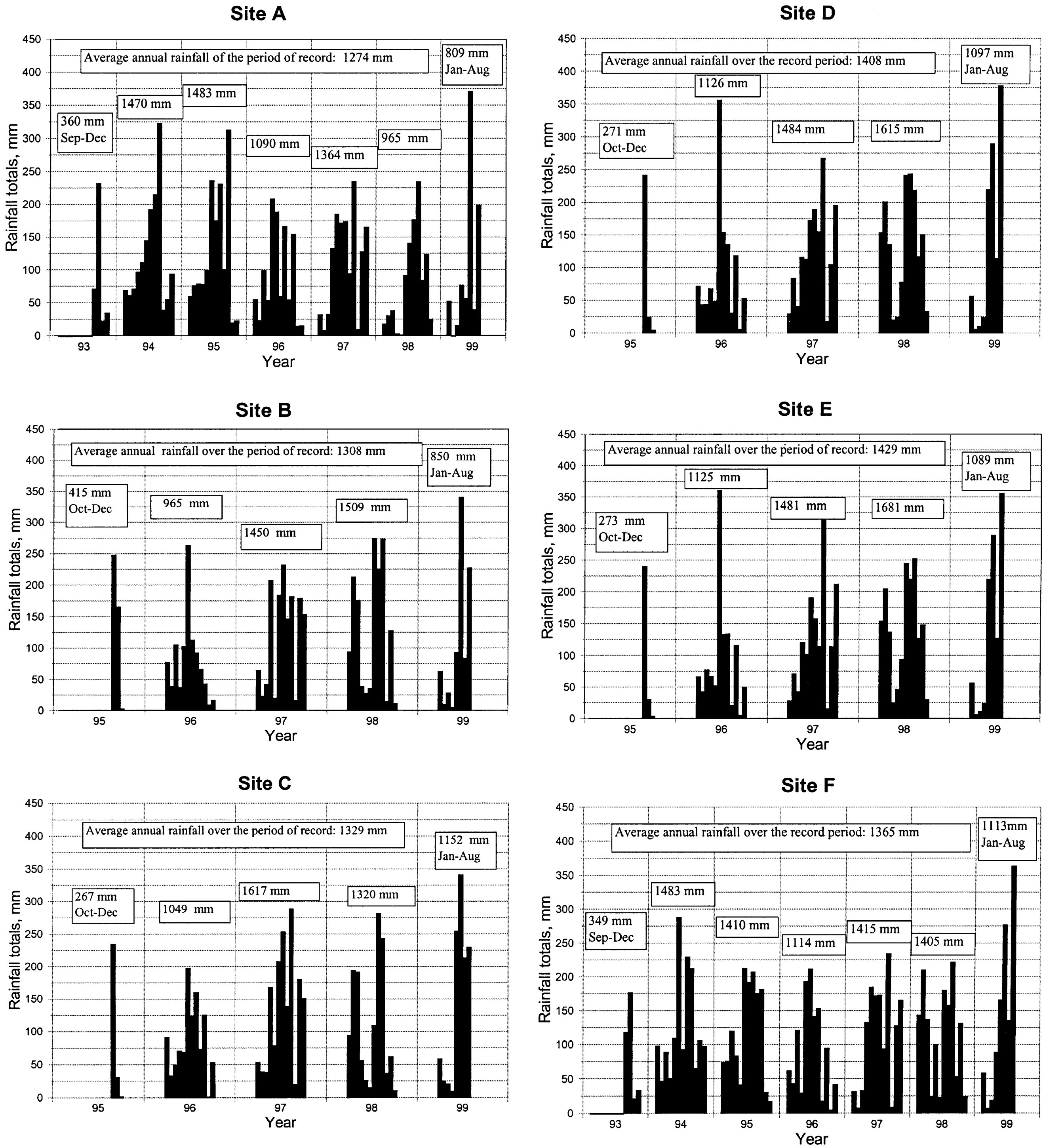


Figure 2–Rainfall totals over the study period: Sites A-F.

In addition to these nitrogen management practices, irrigation management using tensiometers was recommended at all sites, including Site A. Three clusters of five tensiometers were installed at 15, 30, 60, 90, and 120 cm below land surface at each site. Two additional clusters of tensiometers were installed at the 15- and 30-cm depths only. Recommended set points for initiating irrigation were established at –10 kPa (at the 15 cm and 30 cm depths) for January through June and –15 kPa (at the 15 cm and 30 cm depths) for July through December. Tensiometers at the lower depths are used to check the depth of wetting following each irrigation regime.

Tables 4 through 9 summarize the nitrate-nitrogen concentration statistics for each multilevel sampler port, as well as the depth-averaged concentration statistics, for each site. Figure 5 shows the depth-averaged groundwater nitrate-nitrogen concentration time series for each site. Figure 6 shows the average groundwater nitrate-nitrogen concentration time series for each multilevel sampler port at each site. In these tables and figures, Port 1 represents

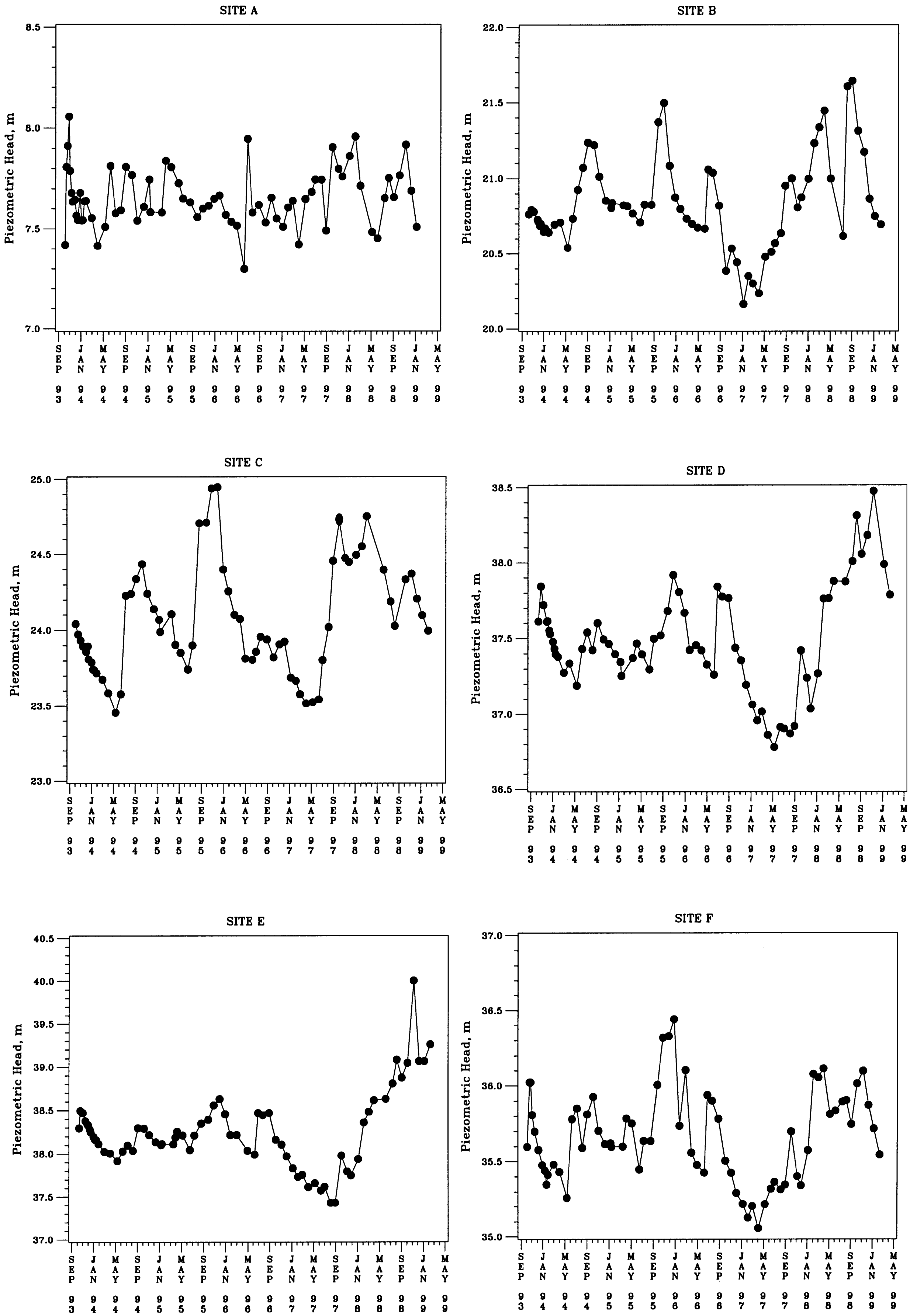


Figure 3–Time series of average piezometric head levels in meters above mean sea level: Sites A-F.

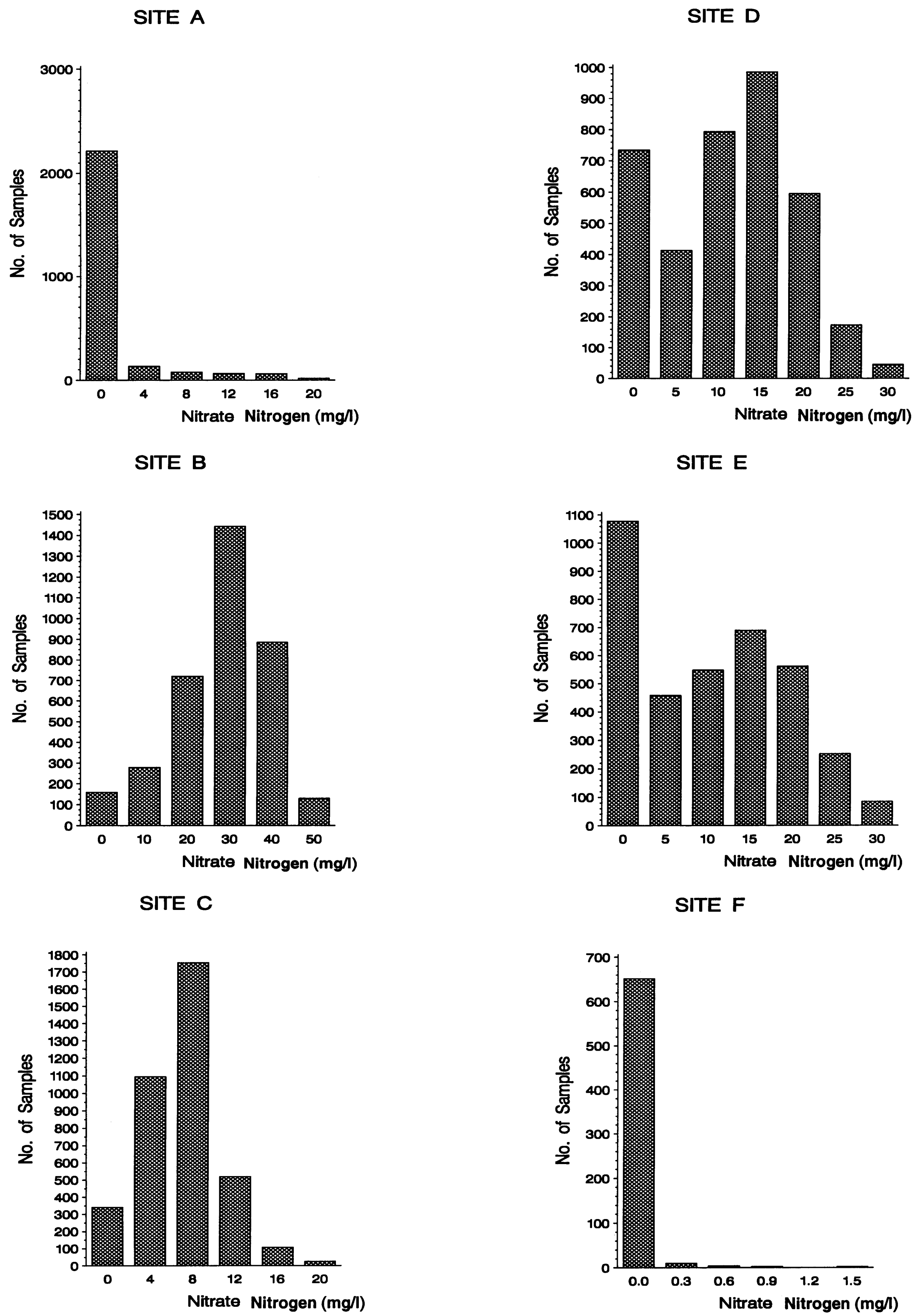


Figure 4–Pre-BMP histograms of groundwater nitrate-nitrogen concentrations aggregated over space and time: Sites A-F.

the top MLS port positioned at the highest expected water table elevation. Ports 2 through 10 represent successively deeper MLS ports, positioned at 60 cm intervals. Thus Port 2 samples groundwater approximately 0.6 m below the water table and Port 10 samples groundwater approximately 6 m below the water table.

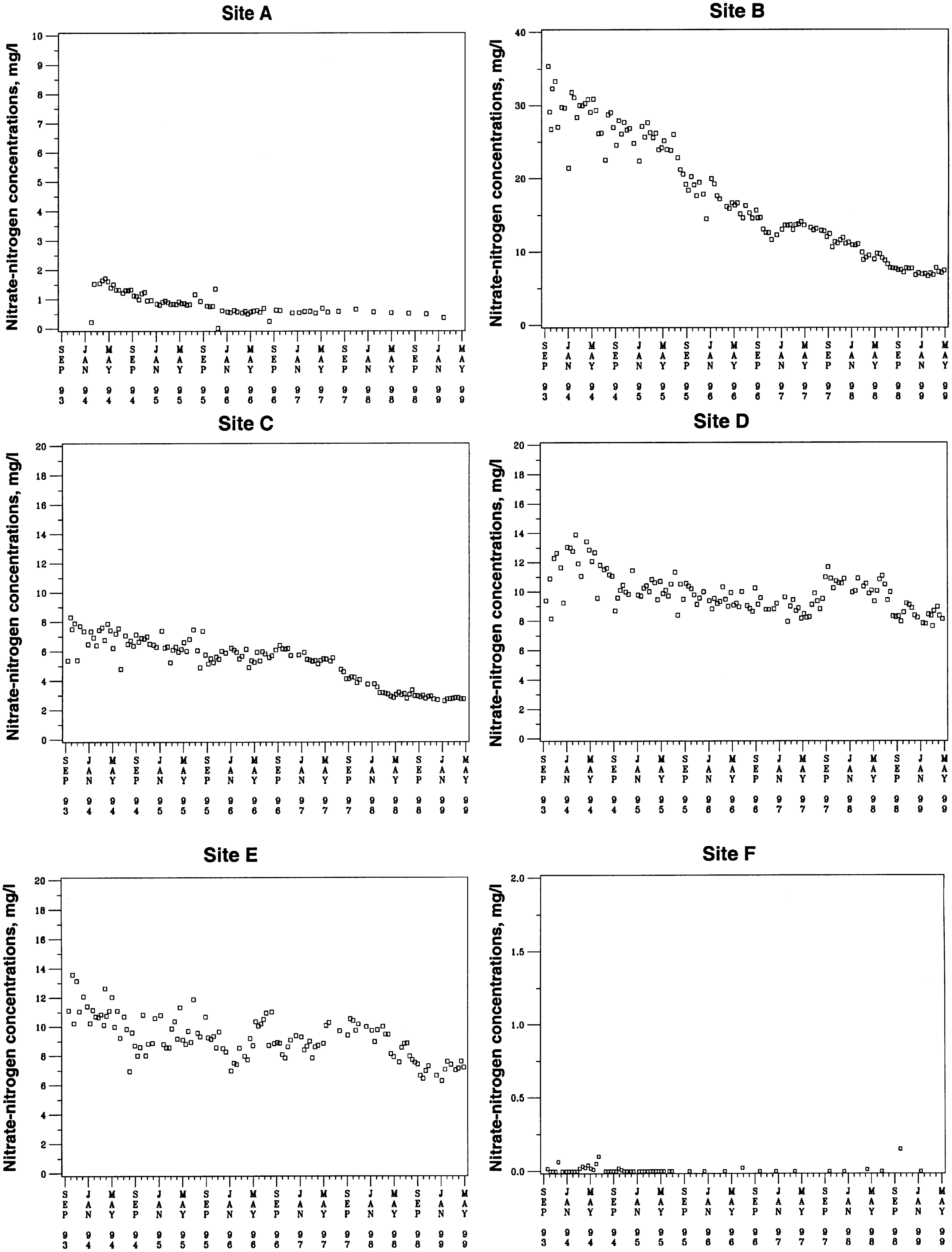
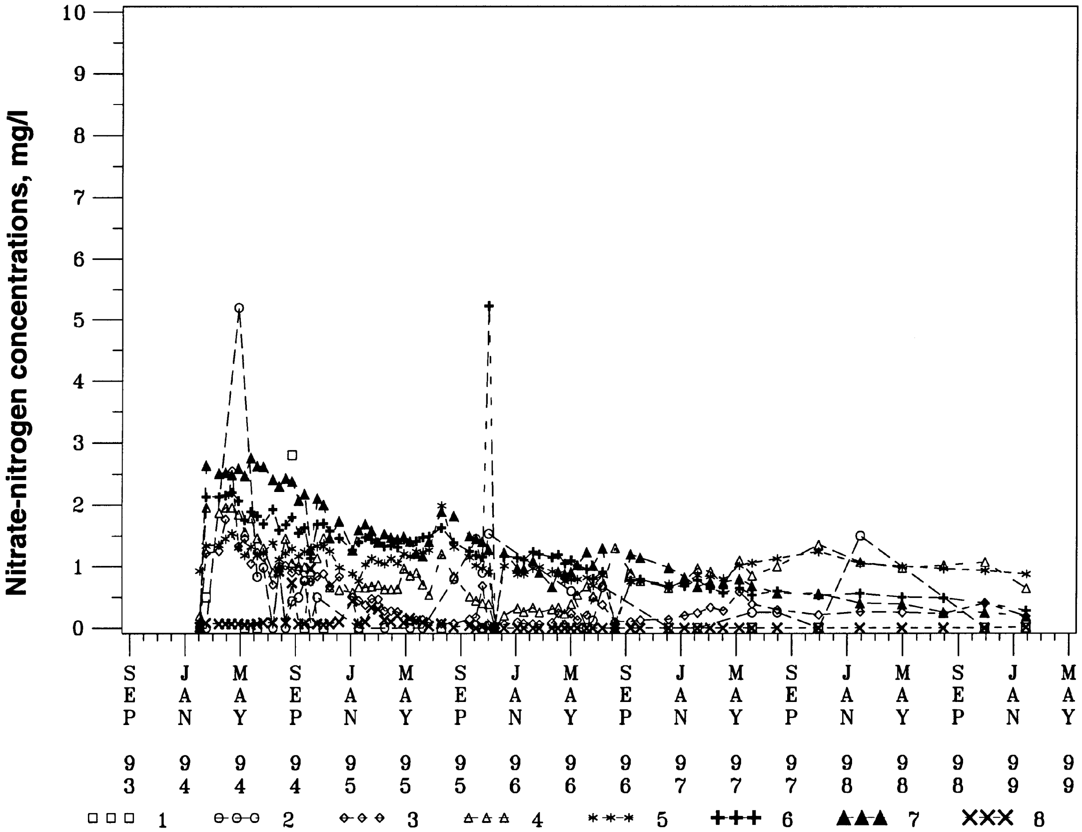


Figure 5–Time series of average nitrate-nitrogen concentration over the top 6 m of the surficial aquifer: Sites A-F.

Site A



Site B

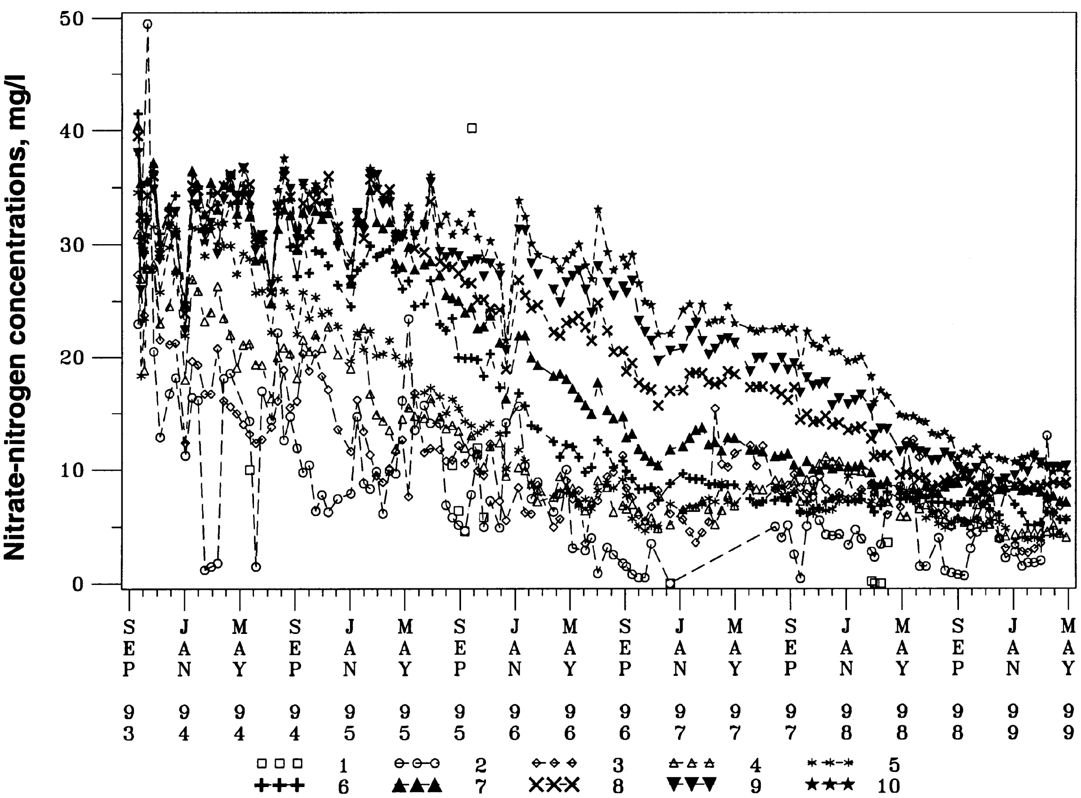
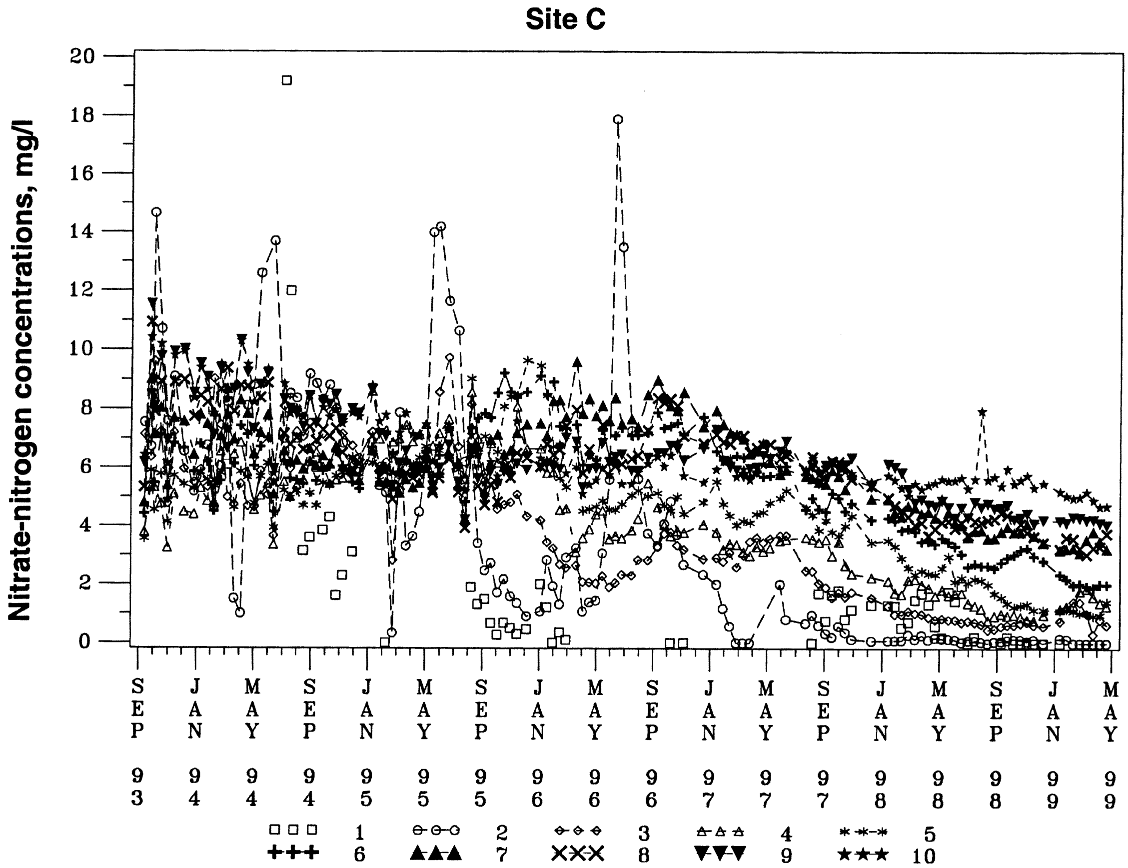


Figure 6–Time series of average nitrate-nitrogen concentration by port number in the surficial aquifer. Port 1 represents the top MLS port positioned at the highest expected water table elevation. Ports 2 through 10 represent successively deeper MLS ports, positioned at 60-cm intervals: Sites A and B.



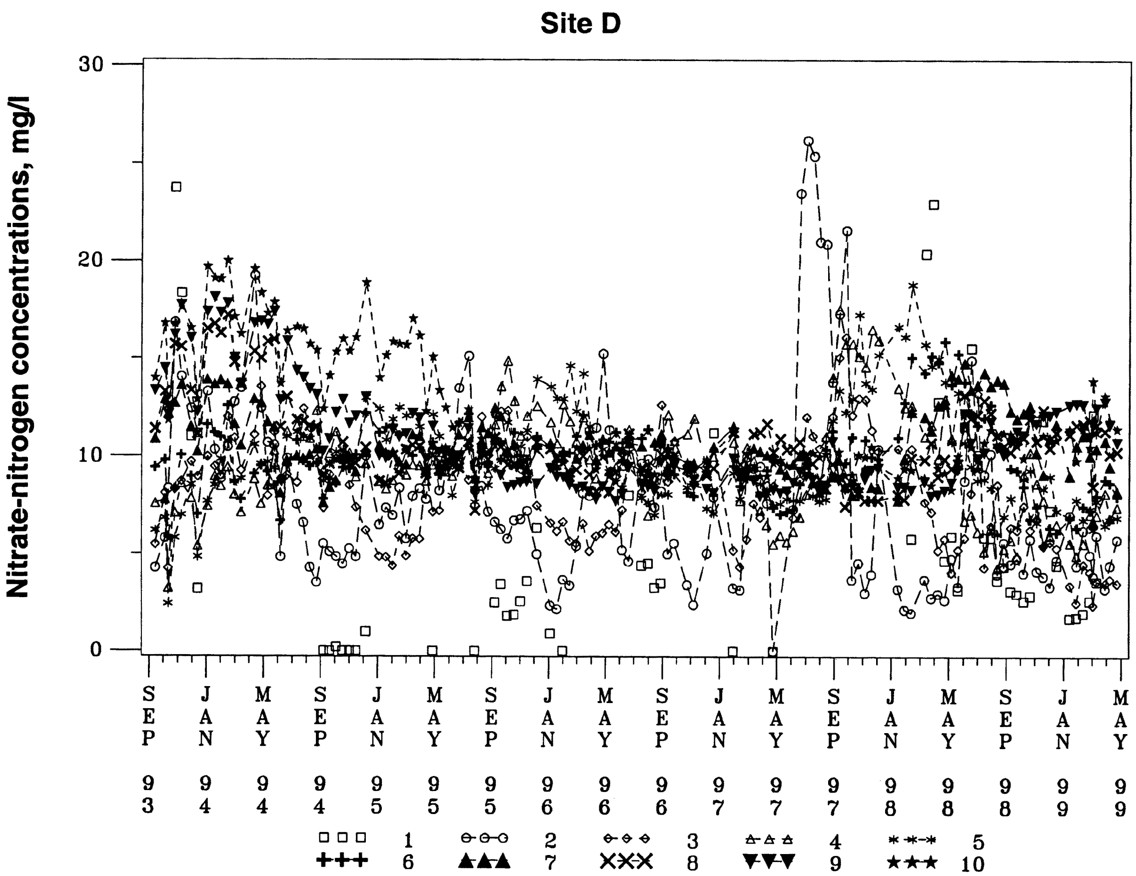
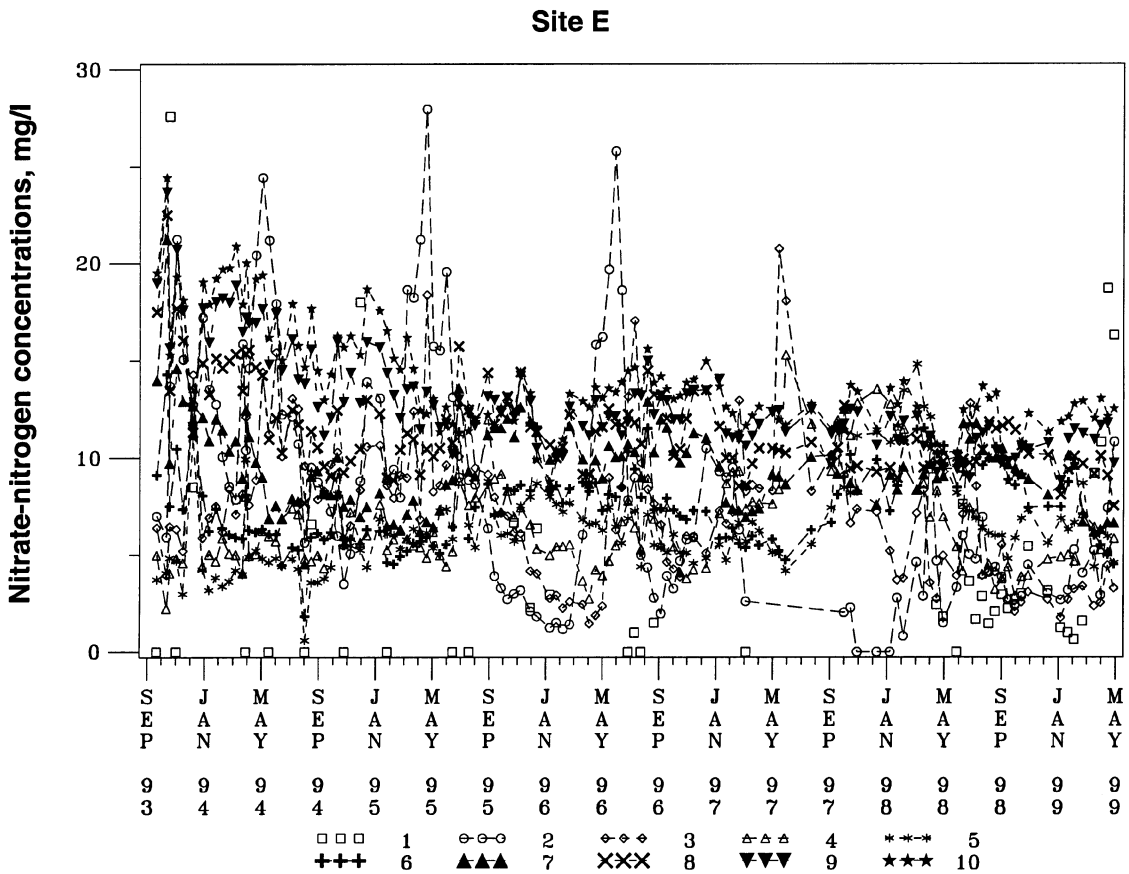


Figure 6 (cont.)–Time series of average nitrate-nitrogen concentration by port number in the surficial aquifer. Port 1 represents the top MLS port positioned at the highest expected water table elevation. Ports 2 through 10 represent successively deeper MLS ports, positioned at 60-cm intervals: Sites C and D.



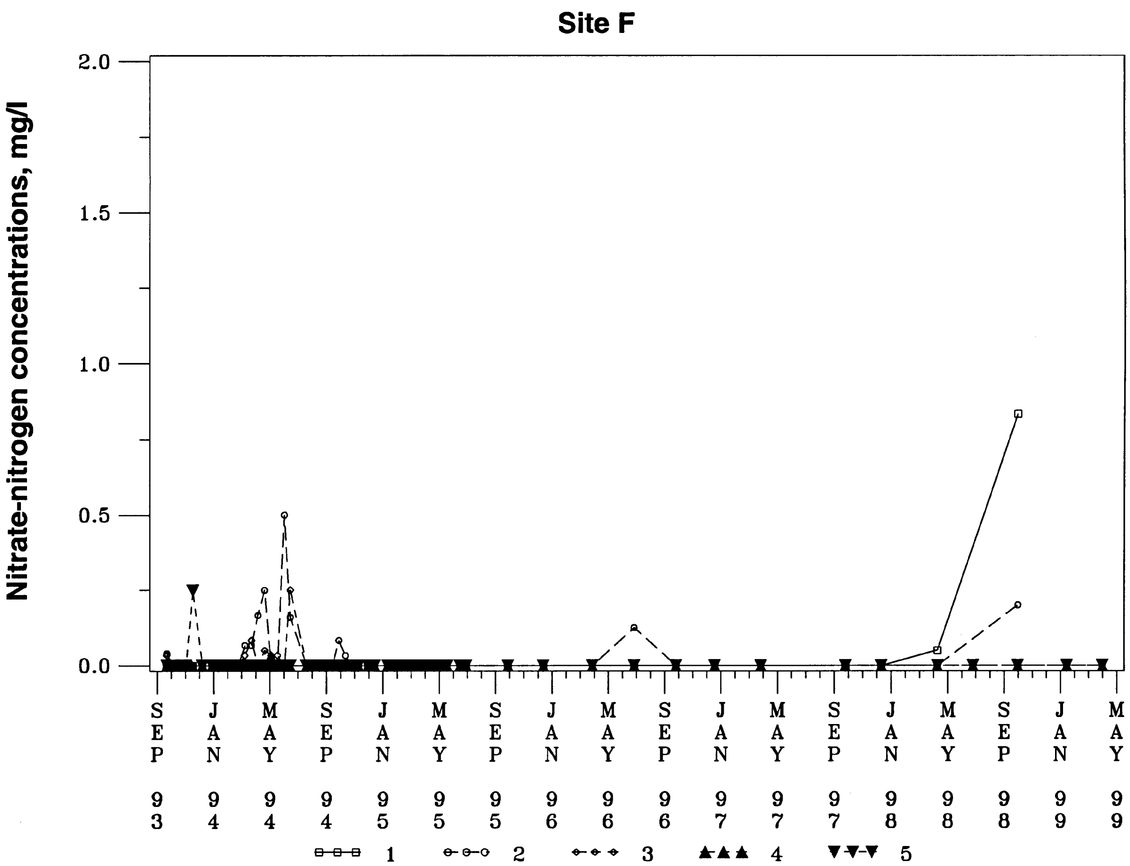


Figure 6 (cont.)–Time series of average nitrate-nitrogen concentration by port number in the surficial aquifer. Port 1 represents the top MLS port positioned at the highest expected water table elevation. Ports 2 through 10 represent successively deeper MLS ports, positioned at 60-cm intervals: Sites E and F.

Table 4, figure 5, and figure 6 summarize data from the native vegetation site on the Central Florida ridge (Site F) and confirm that virtually no nitrate-nitrogen was detected in groundwater at any depth beneath this site. There was no statistically significant downward trend observed for the depth-averaged nitrate-nitrogen time series. The extremely small downward trends observed at Ports 2, 3, and 5 were statistically significant according to the trend analysis, but insignificant for all practical purposes.

Table 5 summarizes the data from the flatwoods grove off the ridge (Site A). These data show average nitrate-nitrogen concentrations were well below the MCL throughout the monitored depth of the aquifer at Site A. A small statistically significant downward trend in the depth-averaged nitrate-nitrogen time series is evident in figure 5. Figure 6 shows that average nitrate-nitrogen concentrations were elevated above 2 mg/L in Ports 4 through 7 (2.4 m to 4.2 m below the top of the water table) at the beginning of the study period, and that these concentrations decreased to at or below 1 mg/L over time. The non-parametric trend analysis indicated statistically significant downward trends in nitrate-nitrogen concentration at Ports 2 and 6 through 8 (see table 5). Note that all the statistically significant downward trends were very small, ranging from –0.06 to –0.52 mg/L-year, with an average downward trend of –0.20 mg/L-yr. Furthermore, since fertilization practices were not changed at this site these minor downward trends in nitrate-nitrogen concentration cannot be attributed to changes in nutrient management practices. A spatial analysis of the individual MLS data revealed two MLSs in the northwest portion of Site A with elevated nitrate-nitrogen in Ports 4 through 7, which slowly decreased over time. The remainder of the MLSs throughout Site A showed virtually no detectable nitrate. Since the two impacted MLSs are in the vicinity of the fertilizer mix and load facility, it is likely that these elevated nitrate-nitrogen concentrations are due to a point-source problem rather than to routine nitrogen application at this site.

Table 4. Groundwater nitrate-nitrogen concentration statistics at Site F

Port	No. of Samples	Mean (mg/L)	Statistical Test Used for Trend Analysis Statistical Test	Slope (mg/L-year)
1	13	0.068	Kendall	N.S.*
2	53	0.032	Kendall	–0.009
3	56	0.009	Kendall	–0.004
4	56	0.001	Kendall	N.S.
5	56	0.004	Kendall	–0.004
Ave	56	0.011	Kendall	N.S.

* N.S. = Not statistically significant at the 95% confidence level.

Table 5. Groundwater nitrate-nitrogen concentration statistics at Site A

Port	No. of Samples	Mean (mg/L)	Statistical Test Used for Trend Analysis Statistical Test	Slope (mg/L-year)
1	17	0.19	Kendall	N.S.*
2	39	0.95	Kendall	–0.26
3	85	0.54	Spearman-Lettenmaier	N.S.
4	87	0.97	Spearman-Lettenmaier	N.S.
5	87	1.07	Spearman-Lettenmaier	N.S.
6	87	1.45	Spearman-Lettenmaier	–0.35
7	87	1.76	Spearman-Lettenmaier	–0.52
8	87	0.14	Kendall	–0.06
Ave	87	0.99	Spearman-Lettenmaier	–0.20

* N.S. = Not statistically significant at the 95% confidence level.

Table 6 summarizes the data from the most heavily impacted mature citrus grove (Site B). In table 6 and all subsequent tables, the pre-BMP mean for each depth is the average nitrate-nitrogen concentration for the period September 1993 through December 1994, while the post-BMP mean is the average nitrate-nitrogen concentration for the period January 1995 through April 1999. Table 6 shows that groundwater nitrate-nitrogen concentration increased systematically with depth in the aquifer during both the pre-BMP and the post-BMP periods. This is an indication that, in both the pre-BMP and post-BMP periods, the water recently recharging the aquifer had lower nitrate-nitrogen concentrations than previous recharge water. This behavior in the pre-BMP period is likely due to the systematic decrease in nitrogen fertilizer that had been applied to this grove in the five years before the project began (see table 1). The continued behavior in the post-BMP period is due to the further significant reduction in fertilizer applied as a result of this project. As indicated in table 6, the post-BMP mean nitrate-nitrogen concentrations were statistically significantly smaller than the pre-BMP nitrate-nitrogen concentrations at all ports, except for Port 1. The Port 1 statistics were not reliable, however, due to high variability in the small number of samples.

A large, statistically significant, downward trend in the depth-averaged nitrate-nitrogen time series at Site B is evident in figure 5. Similar significant downward trends in the time series of average nitrate-nitrogen concentration at each depth in the aquifer are evident in figure 6. As

Table 6. Groundwater nitrate-nitrogen concentration statistics at Site B

Port	Pre-BMP No. of Samples	Pre-BMP Mean (mg/L)	Post-BMP No. of Samples	Post-BMP Mean (mg/L)	H_0: Pre-Mean = Post-Mean*	Statistical Test Used for Trend Analysis	Slope (mg/L-year)
1	1	10.00	12	8.92	NA	Kendall	N.S.†
2	28	13.66	85	6.02	Reject	Kendall	–2.28
3	31	18.18	102	8.24	Reject	Spearman-Lettenmaier	–2.48
4	32	22.54	102	8.78	Reject	Spearman-Lettenmaier	–3.68
5	32	27.07	102	9.23	Reject	Spearman-Lettenmaier	–4.80
6	32	32.02	102	11.97	Reject	Spearman-Lettenmaier	–6.00
7	32	32.60	102	15.11	Reject	Spearman-Lettenmaier	–5.76
8	32	33.06	102	18.36	Reject	Spearman-Lettenmaier	–5.44
9	32	32.25	102	20.76	Reject	Spearman-Lettenmaier	–4.84
10	32	32.16	102	22.88	Reject	Spearman-Lettenmaier	–4.43
Ave	32	27.93	102	14.01	Reject	Spearman-Lettenmaier	–4.64

* Testing the hypothesis that the pre-BMP mean is equal to the post-BMP mean. Decision made at the 95% confidence level.
† N.S. = Not statistically significant at the 95% confidence level.

mentioned previously, fertilizer applications had been steadily decreasing at Site B for five years before this project began. Thus the concentrations of nitrate-nitrogen at the top of the surficial aquifer tend to decrease even prior to BMP implementation. Figure 6 shows a significant stratification of nitrate-nitrogen concentrations over depth, with the lowest values occurring at the top of the water table, indicating recent improvement in recharge water quality. The non-parametric trend analysis showed that nitrate-nitrogen concentrations at Ports 2 through 10 at Site B evidenced statistically significant downward trends that ranged from –2.3 to –6.0 mg/L-year. Port 1 did not show a statistically significant downward trend, because of the sporadic sampling at this port and the large magnitude of the concentration variance at this location. Figure 6 shows that at the beginning of the project nitrate-nitrogen concentrations were above the EPA MCL throughout the upper 6 m of the aquifer. Over the study period the nitrate-nitrogen concentrations began to drop below the MCL, beginning with the shallowest ports near the top of the aquifer, and proceeding to the deeper ports. By April 1999 nitrogen-nitrate concentrations in the top 6 m of the aquifer (measured by Ports 1 through 10) had dropped to, at or below the EPA MCL of 10 mg/L.

Table 7 summarizes the data from the young citrus grove (Site C). These data show that at all depths both the pre-BMP and post-BMP mean nitrate-nitrogen concentrations were below the MCL. However, the post-BMP means were statistically significantly smaller than the pre-BMP means at all ports. Furthermore, the post-BMP data show lower nitrate-nitrogen concentrations at shallow ports near the top of the aquifer, indicating recent improvement in recharge water quality. This supports the premise that the reduction in nitrate-nitrogen concentrations was due to recent changes in nitrogen management practices at this site.

A statistically significant downward trend in the depth-averaged nitrate-nitrogen time series at Site C is evident in figure 5. Similar downward trends in the nitrate-nitrogen concentration time-series for each depth in the aquifer are apparent in figure 6. All of the ports showed apparent visual downward trends beginning after the implementation of the BMPs. The non-parametric trend analysis confirmed statistically significant decreasing trends of nitrate-nitrogen concentration over time at all ports except Ports 1, 6, and 7. Figure 6 confirms that in the last 18 months of sampling groundwater nitrate-nitrogen concentrations became quite stratified, with the lowest concentrations occurring near the top of the aquifer. Port 2, the shallowest port that is consistently below the water table at Site C, was well below the MCL toward the end of the post-BMP period. However this port showed spikes of nitrate-nitrogen concentration above 10 mg/L in May and June of 1994, 1995, and 1996. These spikes, which attenuated fairly quickly to below the MCL, were apparently the result of the first summer rains flushing the vadose zone of residual soil water nitrate-nitrogen.

The time series of the depth-averaged nitrate-nitrogen concentrations at Site D is plotted in figure 5, the time series of nitrate-nitrogen concentration at each depth in the aquifer are plotted in figure 6, and the statistics of these time series are summarized in table 8. These data show that, when averaged over depth, the nitrate-nitrogen concentrations exhibit a small statistically significant downward trend over time, and the post-BMP mean is statistically significantly smaller than the pre-BMP mean. However, the depth-specific data in table 8 show that the non-parametric analysis found no significant trend for any port, and the pre- and post-BMP mean concentrations were not statistically significantly different for ports 1, 2 or 4 through 6.

Figure 6 confirms that there was no clear downward trend in the depth-specific nitrate-nitrogen concentration for any port at Site D. Note that, until May 1997, the nitrate-nitrogen concentrations seemed to be converging toward approximately 10 mg/L throughout the depth of the aquifer. However, from May 1997 through December 1998, a significant pulse of nitrate-nitrogen systematically moved downward from Port 2 through Port 10 at Site D, temporarily increasing the concentrations above 10 mg/L. By May 1999 it appeared that all ports except the deepest two (Ports 9 and 10 measuring nitrate-nitrogen at 5.2 to 6 m below the top of the water table) had again dropped below 10 mg/L. Thus, while on average groundwater nitrate-nitrogen concentrations at Site D were in compliance with the EPA MCL in the post-BMP period, from time to time the MCL was exceeded under the management practices implemented at this site.

The time series of the depth-averaged nitrate-nitrogen concentrations at Site E is plotted in figure 5, the time series of nitrate-nitrogen concentration at each depth in the aquifer are plotted in figure 6, and the statistics of these time series are summarized in table 9. Figure 5 shows a small downward trend in the depth-averaged nitrate-

Table 7. Groundwater nitrate-nitrogen concentration statistics at Site C

Port	Pre-BMP No. of Samples	Pre-BMP Mean (mg/L)	Post-BMP No. of Samples	Post-BMP Mean (mg/L)	H_0: Pre-Mean = Post-Mean*	Statistical Test Used for Trend Analysis	Slope (mg/L-year)
1	12	6.02	47	0.74	Reject	Kendall	N.S.†
2	31	7.69	94	2.45	Reject	Spearman-Lettenmaier	–1.80
3	32	6.45	97	2.87	Reject	Spearman-Lettenmaier	–1.31
4	32	5.48	97	3.76	Reject	Spearman-Lettenmaier	–1.05
5	32	5.35	97	4.33	Reject	Spearman-Lettenmaier	–0.87
6	32	6.13	97	5.41	Reject	Spearman-Lettenmaier	N.S.
7	32	6.75	97	5.83	Reject	Spearman-Lettenmaier	N.S.
8	32	7.58	97	5.53	Reject	Spearman-Lettenmaier	–0.69
9	32	8.37	97	5.65	Reject	Spearman-Lettenmaier	–0.75
10	32	8.43	89	6.09	Reject	Spearman-Lettenmaier	–0.66
Ave	32	6.53	97	4.56	Reject	Spearman-Lettenmaier	–0.85

* Testing the hypothesis that the pre-BMP mean is equal to the post-BMP mean. Decision made at the 95% confidence level.
† N.S. = Not statistically significant at the 95% confidence level.

Table 8. Groundwater nitrate-nitrogen concentration statistics at Site D

Port	Pre-BMP No. of Samples	Pre-BMP Mean (mg/L)	Post-BMP No. of Samples	Post-BMP Mean (mg/L)	H_0: Pre-Mean = Post-Mean*	Statistical Test Used for Trend Analysis	Slope (mg/L-year)
1	12	5.86	47	5.55	Accept	Kendall	N.S.†
2	30	9.06	101	7.58	Accept	Spearman-Lettenmaier	N.S.
3	30	9.20	103	7.87	Reject	Spearman-Lettenmaier	N.S.
4	30	8.91	94	9.95	Accept	Spearman-Lettenmaier	N.S.
5	30	9.02	103	10.13	Accept	Spearman-Lettenmaier	N.S.
6	30	9.36	103	10.02	Accept	Spearman-Lettenmaier	N.S.
7	30	11.09	103	10.50	Reject	Spearman-Lettenmaier	N.S.
8	30	13.02	103	9.94	Reject	Spearman-Lettenmaier	N.S.
9	30	14.52	103	9.67	Reject	Spearman-Lettenmaier	N.S.
10	30	16.45	103	10.63	Reject	Spearman-Lettenmaier	N.S.
Ave	30	11.00	103	9.15	Reject	Spearman-Lettenmaier	–0.42

* Testing the hypothesis that the pre-BMP mean is equal to the post-BMP mean. Decision made at the 95% confidence level.
† N.S. = Not statistically significant at the 95% confidence level.

nitrogen time series at Site E, and the non-parametric trend analysis confirmed that this trend was statistically significant at the 95% confidence level. The post-BMP mean for the depth averaged data was also found to be smaller than the pre-BMP mean at the 95% confidence level (see table 9). The statistical analysis of the depth-specific data showed no significant trend for Ports 1 and 3 through 7, and no difference between the pre-BMP and post-BMP means at Ports 1 and 4 through 7. However, at Ports 2 and 7 through 10 the post-BMP means were statistically significantly smaller than the pre-BMP means, and there were statistically significant downward trends over time. Table 9 shows that, for the post-BMP period, the average concentration over the depth of the aquifer was just below the MCL of 10 mg/L, but that the post-BMP mean nitrate-nitrogen concentration for Ports 8 through 10 at Site E were slightly above 10 mg/L. However, at the current downward trends of approximately –0.8 to –1.2 mg/L-year, the concentrations at these ports should drop below the MCL before the end of 2000, further reducing the average nitrate-nitrogen in the aquifer.

Conclusions

A research project was conducted to evaluate the impacts of alternative citrus nutrient and water management practices on groundwater nitrate beneath vulnerable sandy soils in the ridge citrus region of Central Florida. Fifteen months of baseline data showed that groundwater nitrate-nitrogen concentrations beneath mature groves on the Central Florida Ridge were above the MCL. The data from young citrus had an average nitrate-nitrogen concentration of 6.5 mg/L over the top 6 m of the aquifer within three to five years of planting. Data from a flatwoods grove off the ridge showed nitrate-nitrogen levels well below the MCL, and data from a native vegetation site on the Central Florida ridge showed virtually no detectable nitrate-nitrogen.

Following the baseline monitoring period the following site-specific best management practices (BMPs) were implemented: (1) application of a combination of slow release and dry soluble fertilizer at a rate of 180 kg/ha/yr split into three applications (Site D); (2) application of 18 doses of liquid fertilizer at a rate of 180 kg/ha/yr applied through a fertigation system (Site E); (3) application of 18 doses of liquid fertilizer at a rate of 168 kg/ha/yr applied through a fertigation system (Site C); (4) application of a combination of 18 doses of liquid fertilizer at a rate of 78 kg/ha/yr through a fertigation system and three applications of foliar spray fertilizer at a rate of 64 kg/ha/yr for a total of 142 kg/ha/yr (Site B); and (5) use of irrigation scheduling based on tensiometer measurements to minimize excess leaching.

The most significant decrease in groundwater nitrate concentration occurred at Site B where 142 kg/ha nitrogen was applied as a combination of fertigation and foliar spray. This total nitrogen application rate represented only 57% of the average nitrogen applied over the previous five years at this site, and 68% of the average applied over the previous two years. Groundwater nitrate concentrations

Table 9. Groundwater nitrate-nitrogen concentration statistics at Site E

Port	Pre-BMP No. of Samples	Pre-BMP Mean (mg/L)	Post-BMP No. of Samples	Post-BMP Mean (mg/L)	H_0: Pre-Mean = Post-Mean*	Statistical Test Used for Trend Analysis	Slope (mg/L-year)
1	10	6.07	37	3.74	Accept	Kendall	N.S.†
2	32	11.94	84	7.00	Reject	Kendall	–1.98
3	32	8.88	84	7.22	Reject	Kendall	N.S.
4	32	5.76	92	6.84	Accept	Spearman-Lettenmaier	N.S.
5	32	4.70	92	7.04	Accept	Spearman-Lettenmaier	N.S.
6	32	6.80	92	7.78	Accept	Spearman-Lettenmaier	N.S.
7	32	10.01	92	9.38	Accept	Spearman-Lettenmaier	N.S.
8	32	13.15	92	10.85	Reject	Spearman-Lettenmaier	–0.78
9	32	16.07	92	11.72	Reject	Spearman-Lettenmaier	–1.17
10	32	17.41	92	12.62	Reject	Spearman-Lettenmaier	–1.16
Ave	32	10.07	92	8.45	Reject	Spearman-Lettenmaier	–0.53

* Testing the hypothesis that the pre-BMP mean is equal to the post-BMP mean. Decision made at the 95% confidence level.
† N.S. = Not statistically significant at the 95% confidence level.

decreased at an average rate of 4.6 mg/L-yr at Site B, from an average of over 30 mg/L at the beginning of the project, to less than 10 mg/L at the end of the project (see fig. 5).

A statistically significant decrease in groundwater nitrate-nitrogen also occurred at Site C, which received 168 kg/ha nitrogen applied in 18 fertigation applications. This total nitrogen application rate was equivalent to the rate applied over the previous five years. However, the method of application was changed from dry broadcast to fertigation, and the rate was not adjusted upward as is typically done over the first 10 years of citrus cultivation. Groundwater nitrate concentrations decreased at an average rate of –0.9 mg/L-yr at Site C, from an average of approximately 8 mg/L at the beginning of the project, to approximately 4 mg/L at the end of the project (see fig. 5). The decrease in nitrate-nitrogen concentration at this site may be attributable to both to the increase in nitrogen application frequency, and the increasing rate of nitrogen uptake that is expected as the trees matured. It should be noted that although Site C did not have the lowest yearly N application rate, this site showed the lowest post-BMP nitrate-nitrogen concentrations in the upper most portion of the aquifer (see fig. 6). This behavior is likely due to the fact the Site C is planted at a significantly higher density than any of the other sites (see table 1), and the trees at Site C underwent significant growth over the post-BMP period.

Average groundwater nitrate-nitrogen concentrations decreased at a rate of 0.4 to 0.5 mg NO_3-N/L-yr at Sites D and E, which each received 180 kg/ha nitrogen as dry soluble/slow release and fertigation, respectively. These rates represented 74% of the average nitrogen applied over the previous five years, and 90% of the average nitrogen applied over the previous five years at these sites. Average groundwater concentrations at both these sites began at about 14 mg/L, and oscillated around 10 mg/L over the post-BMP period (see fig. 5). Monitoring data from both these sites indicate that, when applying nitrogen at rates of 180 kg/ha at mature groves, the groundwater may on average comply with the EPA MCL but may exceed this limit from time to time depending on weather and crop uptake conditions.

The advantage of the MLSs installed for this project is that they allow discrete sampling of the groundwater nitrate concentrations over depth in the aquifer, and thus allow for rapid and accurate detection in changes in quality of new water leaching into the aquifer from the vadose zone. However MLSs are generally not used for compliance monitoring by regulatory agencies, because nitrate-nitrogen concentrations measured at the very top of the water table are generally not representative of the water quality which would be obtained from a fully-screened drinking water well. Nevertheless, the average nitrate-nitrogen concentration measured over all 10 ports at each site plotted in figure 5 should be equivalent to what would be measured in a monitoring well screened over the top 6 m of the aquifer. This figure shows that by the end of the study period the average groundwater concentration over the top 6 m of the aquifer was in compliance with the EPA MCL at all sites.

The groundwater quality monitoring data presented here indicate that, on average, all of the BMPs implemented in this project produced statistically significant downward trends in NO_3-N concentrations, and all have the potential to meet the EPA MCL for groundwater. However, due to particular site-specific climatic and cropping conditions encountered, it is always difficult to draw irrefutable conclusions regarding the effectiveness of BMPs using relatively short study periods. At the same time it is also difficult to get funding agencies to commit to long-term monitoring studies, and grower cooperators to commit to holding management practices constant over long periods of time. To overcome these problems, and to extrapolate this data set beyond the climatic conditions and management practices implemented in this field study, computer modeling of the impacts of citrus nitrogen and irrigation management practices was conducted. The results of the computer modeling effort are reported in a companion article (Harrison et al., 1999).

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