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Effects of Dairy Manure Nutrient Management on Shallow Groundwater Nitrate: A Case Study

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Abstract. *The effect of three different liquid manure treatments on irrigated crop nutrient uptake, crop yield, soil water quality, and groundwater quality are investigated for a typical California dairy. Animals are housed in open feedlot barns surrounded by exercise yards (corrals). Flush lanes are used to remove manure, from which solids are separated and sold off-farm. The liquid manure is stored in ponds (lagoons) and applied through the existing irrigation system on forage crops. We contrast conventional manure application practices, which largely ignore the nutrient value of the manure, with targeted manure applications designed to fully replace commercial fertilizer applications and to match the crop nutrient uptake. The targeted manure applications are split into two treatments, one that accounts only for the ammonia-N in the manure, and a second treatment that accounts for both ammonia and organic nitrogen. The three treatments are implemented sequentially in the same two fields over a seven year period. The fields have a loamy sand soil and are border flood irrigated. Shallow groundwater quality monitoring at and immediately below the water table occurred almost continuously throughout* *the seven year period. Grower’s records are used to describe the timing and approximate amount of manure applications and crop management during the conventional treatment period. Detailed crop nutrient uptake, irrigation flow, manure nutrient, and soil nutrient concentration measurements are made at each irrigation during the three year period of targeted manure management. Conventional treatments resulted in elevated nitrate-nitrogen concentration at the water table, averaging approximately 100 mg/l. With targeted manure management, nitrate-nitrogen concentrations at and immediately below the water table were reduced by over 50% in the first two years of targeted manure management. Balancing the nutrient application by also accounting for the organic nitrogen in the manure application further reduced the nitrate levels in shallow groundwater. We show that a detailed field nitrogen balance coupled with a simplified site-specific groundwater model provides a practical tool to predict the impact of these treatments on shallow groundwater quality.*

Keywords. Manure, nutrient management, dairy, corn, winter grain, groundwater, nitrate, nitrogen cycle, groundwater modeling, groundwater quality.

Introduction

California's dairy herd of 1.5 million milk cattle produces large amounts of liquid and solid waste. Freestall facilities with a flushing system for manure removal are now commonly used in the San Joaquin Valley, which houses most of the state's dairy herd. At a typical freestall dairy with approximately 1,000 adult cows, an estimated 7,000 - 10,000 cubic-feet of liquid manure are generated daily from animal manure and wash water (VanEenennaam, 1997; Shultz, 1997; Meyer and Schwankl, 2000). After separating out solids, the liquid manure is typically stored in storage ponds (lagoons), recycled through the flushing system for manure removal from the freestalls, and eventually applied to adjacent crop land. The handling and safe disposal or reuse of liquid and solid manure has recently come under critical scrutiny with respect to the environmental impacts to surface water, air quality, and groundwater resources.

Proper nutrient management is one of several environmental aspects of manure handling. Planning and documentation of nutrient management practices is part of proposed federal regulations for concentrated animal feeding operations to control water pollution (EPA, 2000). Implementation of appropriate nutrient management practices is critical to protecting groundwater resources from excess leaching of salts, nitrates, and pathogens. Groundwater serves as the primary source of drinking water in California's rural areas. It is also an important source of irrigation water. In some areas of California, groundwater recharged on dairy facilities will eventually discharge to surface waters. Therefore, groundwater quality may sometimes also play a critical role in the ecological health of streams and estuaries.

The guiding principle of proper dairy nutrient management is to balance the nutrient cycle without excessive loss to the environment: Nutrients in the animal manure are recycled by applying the manure as a crop fertilizer, matching the nutrient application to the field with the nutrient uptake by the forage crop, thereby returning the nutrients back to the animals via the forage grown around the dairies. The nutrient cycle on a dairy is a delicate and complex system of checks and balances, which are difficult to equilibrate in practice. The nutrient cycle includes all three major nutrients, nitrogen (N), phosphorus (P), and potassium (K), each of which partitions at different rates through the many interfaces of the nutrient cycle. Feed quality, feeding practices, milk production, heifer production, wash water handling, manure handling and storage within the dairy, manure application to crops, soil quality in the field, and agronomic practices (including irrigation practices) all influence the balance of the nutrient cycle. In turn, any of these elements have potentially significant impacts on air, surface water, and groundwater quality. One of the elements of the nitrogen cycle for which relatively few California specific data exist is the nitrogen balance in forage fields receiving liquid manure water through irrigation (Mathews et al., 1999; Meyer and Schwankl, 2000). A better understanding of the nitrogen balance in manure treated fields is critical to developing proper nutrient management practices. These practices should accommodate the climatic, soils, and agronomic conditions of California dairies while protecting the water resources that California's agricultural communities depend on.

Objectives. The objectives of this paper are: a) to determine the nitrogen mass balance for two demonstration fields prior to and during a period of targeted nutrient management; b) to predict impact on groundwater quality based on the field nitrogen balance and compare predictions to measured groundwater quality data. The case study serves as a demonstration of the intrinsic link between nutrient management and groundwater quality.

Methods

We selected a set of two adjacent fields at a typical, cooperator-owned freestall dairy operation in the San Joaquin Valley. The nutrient management field study was initiated in May 1998, while the groundwater monitoring adjacent to these fields began in May 1993. The period prior to 1998 is considered an example for “conventional manure management” practices (control data). Beginning in 1998, manure applications were managed to better match crop uptake (targeted manure nutrient management, TMNM). Two different protocols were established for TMNM. An initial protocol was established in May 1998 and implemented for two years (TMNM 1998/99). The protocol was adjusted in May 2000 to further improve the nutrient balance in these fields (TMNM 2000). Because of the timing of the study, we designate a “crop year” that begins with the corn planting in May and ends with the winter forage harvest in April of the following year. Hence, a March fertilizer application in the “crop year” 1998 actually occurred in March 1999.

In this section, we briefly summarize the manure nutrient management practices, the elements of the nutrient cycling in the field and how they were measured, and the groundwater monitoring. Detailed descriptions of these methods can be found in Harter et al. (1999) and Mathews et al. (1999, 2001).

General Setting: The two fields are located on the low alluvial plains and fans east of the San Joaquin Valley trough in the north-central part of the valley (Merced County). The soils are loamy sand to sand with rapid drainage in the surface soil and low water holding capacity. The groundwater table is very shallow (6 – 10 ft.). As on most dairies in this region, the two fields are used to grow two crops per year for silage, summer corn (*Zea mays* L.) and a winter cereal crop. The fields are border check flood irrigated during the summer. Crop plantings and harvest dates vary from year to year. Corn is typically planted in late April through early June and harvested between mid-August and late September. Winter forage is planted in October and harvested in April. Surface water originating from the Sierra Nevada and distributed through the local irrigation district is used for irrigation water during the summer. Late fall irrigations and winter precipitation (annual average: 15 inches) provide moisture for the winter forage crop. In 1998 and 1999, measured annual irrigation applications were approximately 44 acre-inches per acre. Annual average crop water uptake is 27 inches (corn) and 12 inches (winter grains). Estimated net recharge rates under these fields are nearly two feet per year due to the high soil drainage. Irrigation efficiencies of approximately 50% - 60% are similar to those observed elsewhere in the San Joaquin Valley (Meyer and Schwankl, 2000).

Conventional Manure Management (1993-1997)**:** Historically, storage ponds and land disposal of manure, particularly liquid manure, was introduced as a safe alternative to discharging manure into open surface waters (Meyer et al., 1972). Conventional manure management, however, largely ignores the nutrient value of the manure because of the perceived difficulties in managing the manure as a fertilizer. Conventional manure and nutrient management practices on freestall dairies in the northern San Joaquin Valley have three components: 1. Application of pond water (liquid manure) blended with irrigation water occur in the spring and fall preirrigations (prior to corn and winter forage plantings, respectively). 2.Commercial fertilizer is applied during the growth period of the corn (June and July) and occasionally on winter grains (February or March). 3. Excess pond water is disposed to fields during the winter due to the limited holding capacity of the storage pond. Winter disposals of pond water and preirrigations with blended pond water have typically been applied only to a limited crop acreage of the dairy. During the summer, crop nutrient management relies heavily on commercial fertilizer applications.

***Targeted Manure Nutrient Management 1 (1998-1999*)**: Beginning with the planting of the corn crop in May 1998, the following changes were implemented to better match nitrogen applications with crop uptake: Preirrigations were run without addition of liquid manure (pond water). Winter disposals of liquid manure were also discontinued (this required the expansion of available pond capacity). Spring fertilization at a rate of 80 – 120 lbs/acre was implemented with commercial fertilizer (crop year 1998) and with diluted liquid manure (crop year 1999). Commercial fertilizer applications in the summer were replaced by targeted liquid manure applications such that the *ammonia-N* (NH_4-N) content of the liquid manure would supply the necessary 250 lbs/acre. In this treatment protocol, no credit was given to the nitrogen available to the crop from the *organic N* in the liquid manure.

***Targeted Manure Nutrient Management 2 (2000)*:** In 2000, the treatment protocol was adjusted to not only credit all of the NH_4-N, but also 70% of the measured organic N in the pond water as being plant available fertilizer. Hence, the total amount of pond water applied was further reduced compared to TMNM 1998/99. This protocol required a reliable method for estimating the amount of organic N in the pond water immediately prior to irrigation.

***Measurement of nitrogen application*:** The amount of pond water N applied is measured by determining the flow rate of pond water to the field during the irrigation, the duration of the irrigation, the size of the area being irrigated, and the concentration of NH_4-N and organic N in the pond water prior to and during the irrigation. NH_4-N is determined using a hand-held colorimeter to read the color change resulting from mixing the diluted lagoon water with Nessler's reagent and later confirmed through laboratory analysis. Organic N is estimated from the absorbance reading of the diluted lagoon water and later confirmed through laboratory analysis.

***Measurement of soil nitrogen and plant N uptake*:** Soil samples were taken soon after the winter forage crop was harvested, before most irrigations throughout the corn growing season and after the corn was harvested. Soil samples are taken in one or two subplots within each of three or four irrigation checks. Each composite sample consisted of 12 core samples taken from each of five depths to 4 feet. Ammonia-N and nitrate-N (NO_3-N) is determined after equilibrium extraction of soil with one molar potassium chloride and subsequent determination by diffusion-conductivity (Carlson, 1978). At each of the locations where soil samples are collected, 25 feet of one corn row is cut, weighed, subsampled and weighed, dried and weighed to determine moisture content, ground and submitted to the laboratory for nutrient analysis. These samples are collected on each soil sample date after the corn reaches a height of 12-15". Final harvest samples were collected as field chopped silage blown on the ground at the site of the soil sampling location and sampled for nutrient analysis (Gavlak et al., 1994).

***Monitoring of groundwater nitrate*:** Soil nitrate levels and nitrate levels in the shallow-most groundwater within 15 – 20 feet of the water table is used to validate the estimated nitrogen leaching losses from the root zone. Groundwater nitrate is determined from water samples taken at monitoring wells between and adjacent to the two fields. From 1993 to 1999, two monitoring wells were located downgradient of the two fields (Harter et al., 1999). In April 1999, four additional monitoring wells were constructed downgradient of the two fields for a total of six monitoring wells. The monitoring wells are 25 feet deep for measuring water quality within the upper 15 feet of groundwater. Based on a simplified hydraulic analysis, groundwater sampled from these monitoring wells can be shown to originate predominantly from recharge that percolates from the two fields to the water table (Harter et al., 1999). This was confirmed by the more detailed groundwater modeling analysis (see below).

Results and Discussion

Information about the manure management practices on the demonstration fields for the period from 1995 through 1998 was obtained from the operator. He had recorded the date and approximate amount of pond water applied to the two fields and of the amount of commercial fertilizer applied. Commercial fertilizer in the spring, at a rate of approximately 50 – 80 lbs/acre, was applied only in years when no winter disposal of pond water had occurred. Commercial fertilizer applications with liquid ammonia injected into the irrigation water during the summer typically occurred in five separate irrigations at a rate of approximately 50 lbs/acre per irrigation (total: 250 lbs/acre).

Nitrogen Applications. The amount of manure N shown for the years of conventional practices (crop years 1993 – 1997, Fig. 1) were not measured and are based on estimates of the volume of pond water applied and of the nutrient content of the pond water. The grower reported an average of four diluted or straight pond water applications per year on each of the two fields between late 1995 and early 1998 (crop years 1995 – 1997). Applications include (a) preirrigations with blended pond and irrigation water in the spring and fall prior to crop planting during most (but not all) years, (b) applications during the winter months (usually undiluted), and (c) occasional applications during the corn growing season. Pond water applications varied in the amount but typically ranged from 1 to 4 acre-inches per acre per application. Reported ranges of pond water nitrogen concentration range within an order of magnitude (Meyer and Schwankl, 2000; Mathews et al., 2001), making it difficult to estimate the exact amount of applied N. One third to three quarters of the total N is reported to be in form of NH_4-N. For 1999 and 2000, reliable pond water NH_4-N and organic N measurements are available at our site. Measured pond water concentrations of total N at the time of irrigation averaged 400 mg/l and ranged from less than 200 mg/l in late summer irrigations to over 500 mg/l in the spring and early summer irrigations. NH_4-N to organic N ratios ranged from 1:1 to 2:1. Assuming that pond water N concentrations were similar in previous years, we estimate that the average amount of manure N applied during 1993-1997 was 300 lbs per acre in a typical spring preirrigation (April or May), 200 lbs per acre in a typical fall preirrigation (September or October) and at least 300 lbs per acre in a winter disposal (anytime between December and February, Figure 2a). These estimates should be interpreted very carefully. Actual values and actual average annual N applications may differ substantially due to the large variations in manure N composition and annual scheduling of pond water applications. Commercial fertilizer applications are estimated to average 250 lbs per acre, which is the agronomic rate targeted by the grower. Actual fertilizer applications varied, partly as a result of what the grower perceived as nutrient value of summer pond water applications at that time.

Substantially lower amounts of nitrogen were applied during the 1998-99 crop years (Fig. 1) due to omitting the winter disposals of pond water and by replacing commercial fertilizer with targeted manure applications that explicitly accounted for the NH_4-N content in the liquid manure. Further reduction in nitrogen application has been achieved during the last crop year (2000) by also accounting for the organic nitrogen and assuming that 70% of the organic N is plant available (Fig. 1). Total nitrogen applications dropped from an estimated minimum of 1050 lbs N/acre under conventional management to 670 lbs N/acre in 1998 and 1999, and 420 lbs N/acre in the last crop year. We estimate that the margin of error for the 1998-99 and 2000 totals is 10% - 20% based on the accuracy of flow rate and nitrogen concentration measurements.

Plant Uptake and Field Nitrogen Balance. Corn yields (for silage) averaged 33 tons per acre in 1998 and 31 tons per acre in both 1999 and 2000. These yields are comparable to yields achieved under conventional management practices in nearby control checks (Mathews et al., 1999). Monthly plant nitrogen uptake is estimated from plant samples taken in the corn crop in 1999 and 2000, and in the winter grains at time of harvest. Because yields did not change significantly, it is assumed that plant N uptake patterns are similar between the three treatments. Monthly N applications and plant N uptake are compared for each treatment in

Figure 2. Total crop N uptake averages 290 lbs/acre for corn and 150 lbs/acre for winter grain in crop years 1998 and 1999. Winter grains are assumed to have taken up higher amounts of N prior to 1998 due to the manure applications but without difference in crop yield. We estimate that plant N uptake in 1993-1997 averaged 200 lbs/acre. Based on these data, the annual N balance for the two fields, computed as the difference between applied total N and plant N uptake is +560, +230, and –20 lbs N/acre for the conventional, the 1998-99, and the 2000 treatments, respectively. If we assume that ammonia volatilization losses during the irrigation and in the soil are negligible (within the margin of error of the total N application), and that all surplus nitrogen eventually converts to nitrate, the long-term average nitrate-N concentration in the leachate from the field is 106 mg/l under conventional management and 43 mg/l under 1998/99 treatment (at two acre-feet per acre net annual recharge).

These long-term field integrated nitrate leaching estimates can be compared with soil N levels at the bottom of the root zone and with groundwater nitrate-N concentrations observed in two wells between and downgradient of the two fields (six wells after April 1999, Fig. 3). In the soils, total available nitrate- and ammonia-N in the top 4 feet averaged 240, 230, and 170 lbs/acre in April-September of 1998, 1999, and 2000, respectively. In the lower root zone (3ft. – 4 ft. depth), average NO_3-N concentrations for the same three time periods are 73mg/l, 53 mg/l, and 46 mg/l. These concentration estimates are obtained from total available soil nitrate measurements assuming saturated conditions. Because soils are not actually saturated, these concentrations are minimum estimates of soil nitrate concentrations at the bottom of the root zone. Also, because of large variations in soil nitrate concentrations between preplanting and mid-summer, the differences in soil nitrate concentrations between the three summers are not as significant as it may seem. These data are considered preliminary and data analysis is ongoing.

Groundwater Nitrate-N. Average shallow groundwater concentrations of nitrate-N increased between 1993 and 1995 and reached levels between 80 and 120 mg/l during 1995 through 1997. After the last winter pond water application in crop year 1997, the nitrate-N concentrations significantly decreased. Average nitrate-N concentrations fell below 50 mg/l during the crop year 2000 with individual well concentrations ranging from 30 to 65 mg/l during the summer and fall of 2000. The dynamics of the decline in groundwater nitrate concentration agrees well with groundwater modeling results that are based on the following assumptions:

- nitrate concentrations in recharge are equal to the balance of the field N budget dissolved in the net recharge, i.e., 106 mg/l prior to April 1, 1998, and 43 mg/l thereafter (ignoring the last crop year)
- denitrification in the unsaturated zone is considered negligible.
- denitrification in this shallow-most part of the aquifer is assumed negligible.

Predicted groundwater concentrations are within a factor 2 of the concentrations measured in the groundwater monitoring network and those measured at the bottom of the root zone. The modeling results should be interpreted very carefully: (A) Significant amounts of N are stored from year to year in the soil. Organic N pools in the soil that accumulated as a result of years of excess manure applications may only slowly decay as management practices change. The organic N pool may provide a residual source of nitrate in percolating water. (B) Travel times across the individual field to the monitoring wells are on the order of one to several years. Hence changes in the amount of nitrate percolating from the soil may not be detected in groundwater for months or years as indicated by our modeling results (Fig. 3). (C) Denitrification and dilution may reduce groundwater nitrate concentrations relative to the nitrate concentration in the percolating water. Here these effects may be masked by the uncertainty about actual N applications prior to 1998. (D) The installation of subsurface tile drains below the two demonstration fields at the beginning of crop year 1999 may have influenced the nitrate concentrations in the wells through local changes in the groundwater dynamics. We are currently evaluating these impacts.

For 2000, the computed net nitrogen deficit is smaller than the margin of error of the individual budget components. From a practical point of view, inputs and outputs are therefore balanced. However, a balanced budget at the field or farm scale is – by itself - not a guaranty for either environmental compliance or sufficient crop fertilization. Within a field, significant local imbalances may exist due to irrigation nonuniformity, N application nonuniformity (a result of variable pond water N concentrations, and settling of organic suspended solids during manure irrigations), and due to variable irrigation practices from application to application. The soil nitrate concentrations, for example, do not show the drastic decrease anticipated from the field N balance. Continued soils and groundwater monitoring will be necessary to evaluate the actual long-term impacts of the improved management practices on crop yields and groundwater quality.

Conclusion

- Management of manure as the almost exclusive source of crop nitrogen is feasible without short-term impacts on crop yields. Substantial capital improvements in pond storage and pond water delivery to the fields (pump, pipeline extension, flow meter, throttling valve, field test supplies for ammonia and organic N determination) and significant efforts in monitoring the applications are needed to successfully implement these practices.
- Significant reductions in shallow groundwater nitrate concentrations have been achieved. These changes occurred over a relatively short time period due to the high net recharge rate, the high soil permeability, and the extremely shallow water table (less than 10 feet). In areas with deeper water table (50 feet and more), similar changes in groundwater nitrate concentrations near the water table may not be observed until several years after management practices have changed.
- Organic nitrogen must be accounted for to balance the nutrient inputs and outputs to and from the field.
- Long-term studies are needed to evaluate the intermediate and long-term agronomic, environmental, and economic feasibility of the proposed management practices.

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FIGURES:

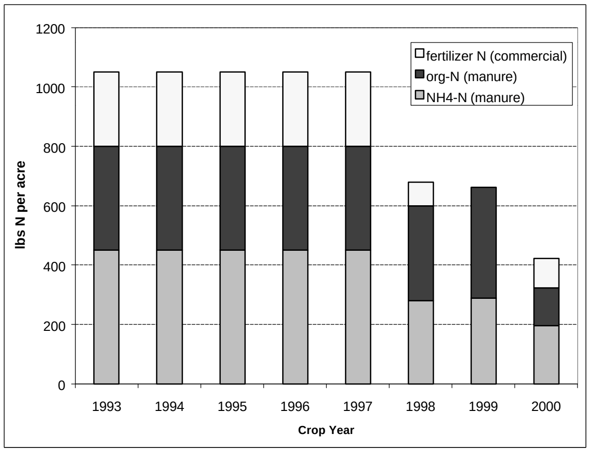
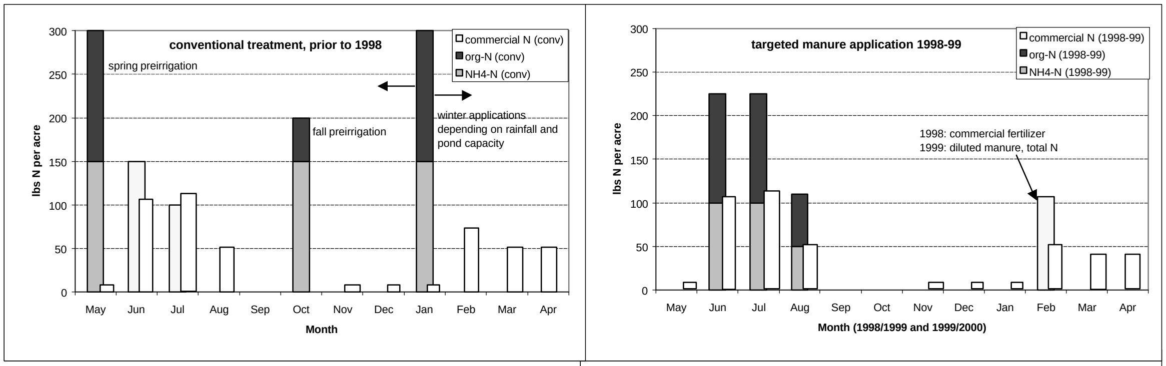


FIGURE 1: Annual nitrogen applications from manure (NH_4-N and organic N) and from commercial fertilizer from 1993 – 2000. Applications for 1993 – 1997 are preliminary estimates based on management practices reported by the cooperator and based on estimates of the NH_4-N and organic N in pond water.



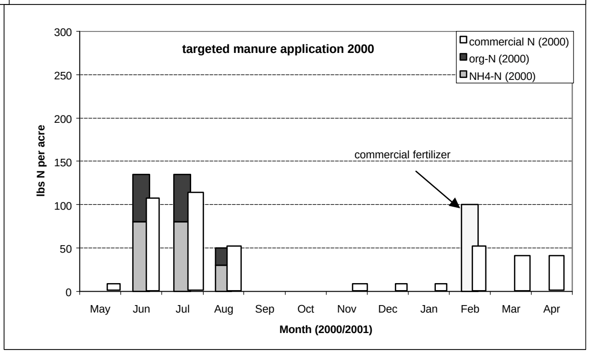


FIGURE 2: Typical monthly nutrient applications (lbs/acre per month) for conventional (a), 1998-1999 (b), and 2000 (c) treatments. In white bars: typical plant N uptake (lbs/acre per month), assumed to be similar throughout all treatments.

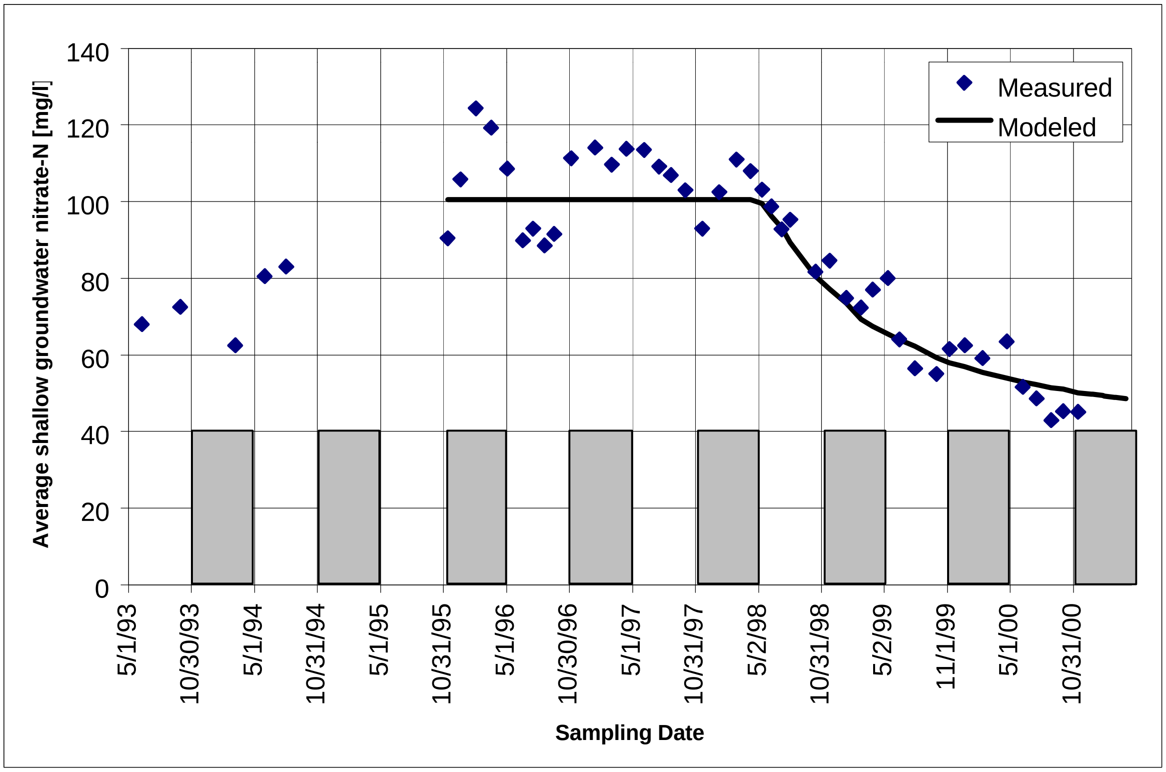


FIGURE 3: Average measured and modeled groundwater nitrate-N from 1993 through 2000. Two wells were monitored throughout that period. Four additional wells were installed in April 1999 and are included in the average. Shaded areas represent winter periods (November through April).