# Nonpoint Source Pollution from Animal Farming in Semi-Arid Regions: Spatio-Temporal Variability and Groundwater Monitoring Strategies [1]

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**ABSTRACT**

Nitrate contamination remains a ubiquitous groundwater pollution problem worldwide. Animal farming systems are among the major sources of groundwater nitrate. Little is known about the impact of dairy farming practices on water quality in the extensive alluvial aquifers underlying many animal farming regions in the United States and elsewhere. The objective of this work is to characterize and assess nitrate leaching across an array of potential point and nonpoint sources within dairy facilities. Sources are divided into three major groups (animal housing areas, liquid manure storage ponds, irrigated fields receiving liquid manure). A shallow groundwater monitoring network (79 wells) was installed on five representative dairy operations in the San Joaquin Valley, California. Nitrate and reduced nitrogen was measured over a four-year period at intervals of 4 - 7 weeks. Reduced N was only found near manure storage ponds. Total nitrogen (N) concentrations are found subject to large spatial and temporal variability within individual dairies, while the range of observed groundwater N was similar on all five investigated dairies. Average shallow groundwater N concentrations within the dairies was almost three times as high (64 mg/l) as immediately upgradient of these dairies (24 mg/l). Nitrogen may vary rapidly over time at individual observation wells. Temporal correlation is insignificant for measurements taken more than 4 to 6 months apart. Spatial distribution of shallow groundwater N across individual dairies is highly complex. Correlation scales are less than 100 m. High spatio-temporal variability severely limits the value of individual groundwater observation wells for compliance monitoring.

## INTRODUCTION AND BACKGROUND

Manure nutrient management is a key component of recently proposed federal regulations (U.S.EPA, 2000) for concentrated animal feeding operations (CAFOs). In California, dairies are the largest CAFO industry with a total herd size of 1.5 million dairy cows. Current liquid and solid waste management practices on dairies have come under scrutiny for their environmental impacts. Among

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those, groundwater quality is a particular concern due to the location of most dairies in low relief (flat) basins (Central Valley, Imperial Valley, Chino Basin, see Fig. 1). The alluvial and fluvial basin fill aquifers of these large watersheds ($10^3$ - $10^5$ $km^2$) are a major source of irrigation water and the almost exclusive source of domestic and municipal drinking water. Agricultural activities in general and dairy operations in particular have been identified as a potentially significant source of nitrate contamination in these aquifers (Lowry, 1987; Mackay and Smith, 1990; Burow et al., 1998; Wildermuth Env. Inc., 1999). However, little is known about the complex link between animal feeding operations (AFOs) and groundwater in semi-arid climates dominated by irrigated agriculture. As a result, no guidance exists on how to effectively manage and monitor groundwater quality within AFOs. The objective of this paper is to provide and discuss representative field data that characterize shallow groundwater quality under the immediate influence of dairies, each comprising a multitude of potential nutrient sources, particularly nitrate. The dataset is used to quantify the spatial and temporal variability of nitrate concentrations in shallow groundwater. We discuss the significance of the results with respect to monitoring potential groundwater quality impacts from dairies.

Dairies comprise a complex conglomeration of multiple potential point and diffuse sources for nitrate contamination of groundwater. Dairies in the Western U.S. commonly use flushed freestalls in open barns, surrounded by uncovered corrals (exercise yards, animal holding area) (Meyer et al., 1997). Manure in the freestalls is flushed utilizing recycled water from the liquid manure storage lagoon (henceforth referred to as "pond"). Manure solids from the flush and those scraped off corral areas are separated from the liquid portion in settling basins or by using mechanical devices. Solids are stored on-site for composting, land application, use as bedding material, or for later off-site delivery. New wash water from the milk barn and winter runoff from the corrals is added to the waste recycling system, thus gradually filling the manure pond (particularly during the wet winter months).

The diluted liquid manure is applied by gravity or pumping to forage crop land adjacent to the pond via the existing flood or furrow irrigation system (Schwankl et al., 1996; Meyer et al., 1997). Manure applications typically occur during the late fall to create pond storage capacity for the winter, during the rainy winter months if runoff collection exceeds pond storage capacity, in the spring during pre-irrigation, and intermittently on summer crops. Irrigated crop land is a large part of a typical dairy (several tens to a few hundreds of hectare). Most dairies grow corn (maize) silage during the summer followed by fall planting of cereal grains (oats, *Avena sativa*, wheat, *Triticum sp*., or barley, *Hordeum sp.*), which is harvested as forage in early spring. Alfalfa (lucerne, *Medicago sativa*) or other crops are sometimes rotated with the corn and may receive applications of diluted liquid manure. Dairy operators have commonly managed manure land application as a waste disposal system, not as a nutrient management system due to inherent difficulties in quantifying the nutritional benefit of the diluted liquid manure. Often, commercial fertilizer is applied in addition to manure to meet the perceived nutrient requirements of the crop (Schwankl et al., 1996; Meyer et al., 1997; Mathews et al., 1999).

In these AFO systems, potential sources of nitrate in groundwater include freestalls, corrals, underground pipelines and storage facilities of the waste recycling system, the manure solids storage area, the feed storage area, settling and liquid manure storage ponds, land application of manure, and commercial fertilizer applications on crop land (with associated irrigation and application nonuniformity). Septic systems for one or several on-site residences are also a potential source of groundwater nitrate. Sources of groundwater nitrate in non-animal farming facilities surrounding these dairies are residential septic systems and commercial fertilizer applications. Upgradient urban areas (golf courses, septic systems, municipal waste application) are another potential source of groundwater nitrate. Most of these potential sources leach at time-varying rates. Hence, the AFO system as a potential "nonpoint" source of water pollutants is in fact a complex system of point and distributed sources of spatially and temporally very variable source strength. While it is impossible to characterize the contributions of these sources in detail, we conceptualize the dairy as consisting of three major management units (Harter et al., 2001a): corrals (feedlots, freestalls, flush alleys, etc.), ponds, and crop fields. In this paper, we investigate the variability of shallow groundwater nitrate between dairies, between the three management units within the dairies, and quantify spatial and temporal correlations using geostatistical and time series analysis. The analysis provides the basis for a discussion of monitoring options.

## METHODS

***Study Sites.*** For this study, five commercial dairy facilities with an average of approximately 1,000 animal units and of 60 ha crop fields per dairy were selected for groundwater quality monitoring. A monitoring well network was established in 1993, hydrogeologic conditions were measured to estimate the monitoring well source area, and a long-term groundwater quality monitoring program was established. The selected dairies are on the east side of the valley trough in the northern San Joaquin Valley (Fig. 1), where the water table is shallow (less than 5 m), and soils are predominantly sandy. The climate in this region is mediterranean with annual precipitation of 290 mm, practically all of which occurs between October and April. Summers are dry and hot. The area is characterized by featureless topography with slopes of less than 0.2%. Historically, border flood irrigation of forage crops has been dominant among AFOs in this region. The dominant surface texture at our study sites is sandy loam to sand underlain by silty lenses, some of which are cemented with lime. Some soils may have a slight accumulation of clay in their subsoil. Water holding capacity is low. Groundwater in the alluvial sediments generally flows from the east-northeast to the west-southwest following the slope of the landscape. The average regional hydraulic gradient ranges from approximately 0.05 to 0.15%. The water table at the selected facilities is between 2 m and 5 m below ground surface. Hydraulic conductivity ($K$) of the shallowest aquifer material has been estimated from slug tests. The $K$ values range from $10^{-4}$ to $2*10^{-3}$ m/s (Davis, 1995), which is consistent with the predominant texture of the shallow sediments.

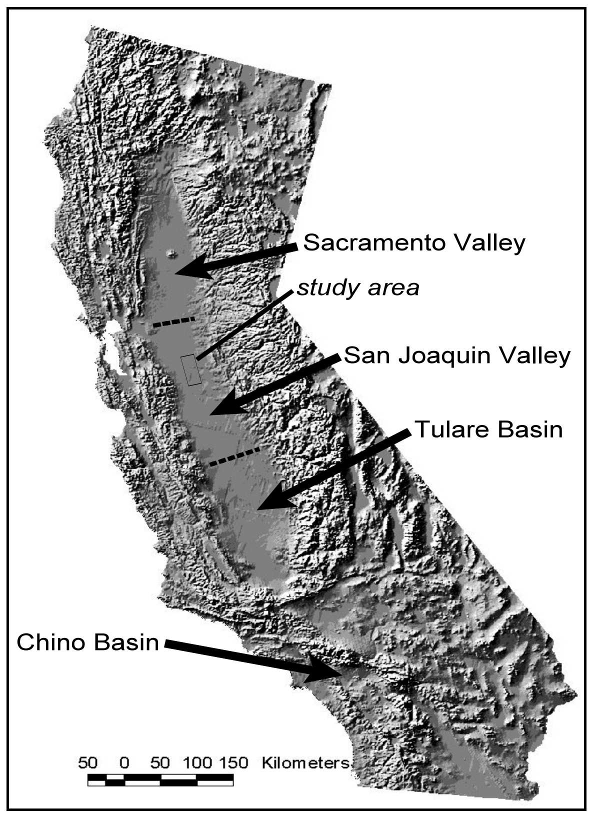


**Figure 1**: Digital elevation map of California indicating the location of the study area and the major dairy basins in the state.

***Monitoring Network.*** On each dairy, between 6 and 12 shallow groundwater monitoring wells were installed for a total of 44 "RWQCB" wells. These wells were monitored for a seven-year period. From June 1993 through August 1994, preliminary well samples were taken on an approximately three-monthly basis. From November 1995 through November 1999, well samples have been taken on an approximately five- to six-weekly basis. Monitoring wells are strategically placed a) upgradient and downgradient from fields receiving manure water, b) near wastewater lagoons (ponds), and c) in corrals, feedlots, and storage areas (henceforth referred to as "corrals"). In the spring of 1999, an additional 35 monitoring wells were installed on two of the dairies ("UCD" wells). The locations of the additional wells were selected to provide a denser network of shallow groundwater quality immediately upgradient of the two facilities, and within their field and corral areas. Wells are constructed with PVC pipe and installed to depths of 7 - 10 m. The wells are screened from a depth of 2 - 3 m below ground surface to the bottom of the well. Water samples collected in the monitoring wells are therefore representative of only the most shallow groundwater. Shallow groundwater on these dairies originates primarily from percolation of excess irrigation water (including manure water) applied within and adjacent to the dairies. Based on hydraulic data we estimate that the source area (the land area from which the well water originates) extends from one hundred to several hundred meters upgradient from each monitoring well.

***Sampling Protocol.*** At each sampling campaign, groundwater levels are determined, the well is purged with a minimum of 5 well volumes or after field water quality (pH, EC) stabilizes, and water samples are collected. Water samples are cooled and stored at 1ºC for analysis of $NO_3$-N and total Kjehldahl nitrogen (TKN). TKN is a measure of total reduced nitrogen, the sum of ammonium-N and dissolved organic nitrogen in the water samples. For quality control, blank, duplicate, and diluted duplicate samples are prepared in the field from approximately every 10th well water sample. $NO_3$-N determination is by diffusion-conductivity analyzer (Carlson, 1978). Total Kjeldahl Nitrogen is determined by the wet oxidation of $H_2O$ using standard Kjeldahl procedure with sulfuric acid and digestion catalyst (Keeney and Nelson, 1982).

## RESULTS AND DISCUSSION

The statistical analyses are carried out for the sum of measured $NO_3$-N plus measured TKN concentration, denoted hereafter as nitrogen (N). Unless otherwise mentioned, TKN concentrations are negligibly small for purposes of this study (less than 3 mg/l), and N concentrations are equal to $NO_3$-N concentrations. The observation period we selected for the analysis is November 1995 through November 1999.

***General observations***. Nitrogen concentrations of the dairy wells (not including those wells upgradient of the dairies) show considerable variability. The coefficient of variation is 60% (1234 observations). The individual 4-year arithmetic mean nitrogen concentrations at each of the wells range over more than one order of magnitude giving witness to the large spatial variability between observation wells. The difference between the 75$^{th}$ percentile and the 25$^{th}$ percentile in the distribution of the measurements at individual wells also varies over more than one order of magnitude, demonstrating the large temporal variability of groundwater nitrate concentrations. The differences in groundwater nitrogen concentrations between the five dairies (not including upgradient wells) are small compared to the spatial and temporal variability of concentrations within each dairy. The mean concentrations obtained by averaging all measurement data from individual dairies differ by less than a factor 2 while the range of concentrations found on each dairy overlap considerably. Analysis of Variance (ANOVA) on the 4-year average mean N of individual wells shows that differences between dairies are not statistically significant (Harter et al., 2001a). For purposes of further statistical analysis,

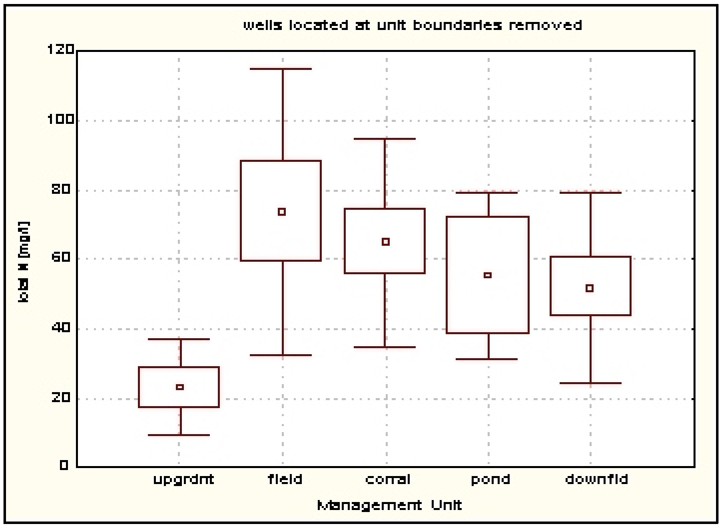


**Figure 2**: Mean (small square), standard error of the mean (large box, and standard deviation of total N in groundwater, by management unit. Field wells are divided into those upgradient of the corral ("field") and side- or downgradient from the corral ("dwnfld") to create a statistical profile through the dairy facility.

we therefore consider all dairies to be from the same statistical sample population.

***Effect of dairy management unit:*** To differentiate nitrate groundwater loading from various management units within each dairy, monitoring wells are grouped by the management unit immediately upgradient of each well, regardless of the presence of other management units within the potential estimated source area (further upgradient or immediately downgradient). The three dairy management units considered are corrals, ponds, and fields (see above). All "field" wells are downgradient of fields that are used for either regular or intermittent application of liquid manure. Wells immediately upgradient of the dairy property are considered to belong to a separate "upgradient" management unit. Surprisingly, the mean N does not vary significantly across the three dairy management units (Fig. 2). The spatio-temporal variability (coefficient of variation of all observations) is also similar for the dairy management units. Only the 'upgradient' (non-dairy) monitoring wells show significantly smaller average N concentrations. Average 'upgradient' nitrate levels are approximately one-third of the average concentration observed within the dairies indicating a large N contribution from the dairy itself.

In contrast to the statistical distributions of total N, which show no significant differences between dairy management units, measurable TKN concentrations (5 mg/l or more) were detected at only four wells. Three of these four wells are located within the downgradient outside slope of the berms of three separate ponds indicating that some of these earthen ponds leach, at least locally. Pond leaching is estimated to be on the order of 1m/year (Harter et al., 2001a)

***Spatial variability within operations.*** A geostatistical analysis of nitrate-N distribution was implemented on two neighboring dairies with 45 wells (RWQCB wells and UCD wells). These are distributed over an area that extends 1.6 km in E-W direction and approximately 0.8 km in N-S direction. Well spacing in N-S direction ranges from 60 m to 400 m and two pairs of wells that are approximately 30 m and 45 m apart. Well spacing in E-W direction (approximate groundwater flow direction) is mostly 200 m and 400 m with a one pair 45 m apart and several pairs approximately 100 m apart. One well was drilled within 3 m of another well for replacement. Concurrent samples were taken from both wells prior to abandoning the older well. Sample nitrate agreed to within 5%. Variogram analysis (Isaaks and Srivastava, 1989) was implemented on the April and September 1999 sampling data to characterize spatial correlations, an important measure for determining the efficiency of a monitoring well network. An omnidirectional Gaussian variogram model (Fig. 3) was fitted to the two datasets with a nugget of 0.65, a sill of 1.25, and a range of 900 m (3,000 ft).

Based on physical observations at the most closely spaced well pairs, and based on the geostatistical observations, we suggest that three scales of variability can be distinguished: variations of approximately 5%-10% of the observed concentration may occur withiny a couple of meters as shown by the closely space well pair and as shown by the consistency of the water quality when pumping large amounts of water from a single monitoring well. Larger variations with some persistent spatial continuity occur at a scale of 50 - 300 m, which is the scale of a field or corral area. Even larger variability is observed at the farm scale (900m - 1,600 m). From a statistical point of view, this last scale is not well developed due to the fact that 800 m is one-half of the largest length scale of the observation network. This largest scale reflects an overall concentration profile with a “low-high-less high” division from the upstream to the downstream end of the dairy and reflects approximately half of the overall variability. From a practical point of view, the geostatistical analysis suggests that individual monitoring well data from these very shallow groundwater systems are representative of only an extremely small area (several tens of square meters) and grossly indicative of shallow groundwater nitrate concentrations within an area of perhaps 1 - 5 hectare.

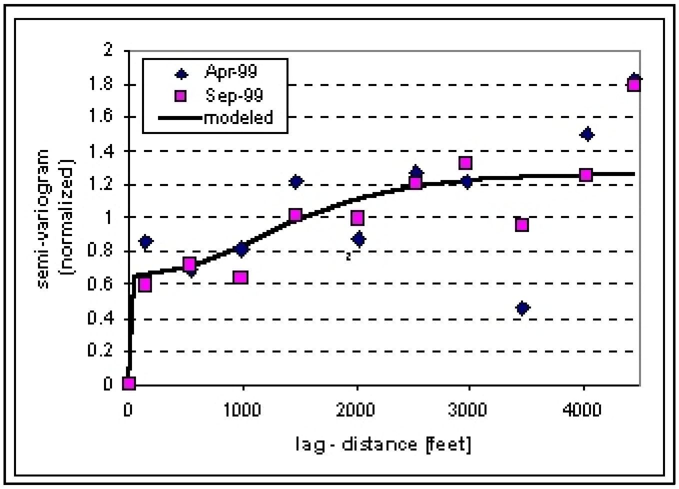


**Figure 3**: Sample semi-variograms of $NO_3$-N concentrations in April and September 1999. The modeled semi-variogram is a Gaussian model with a range of 1,500 m (5,000 ft), a nugget of 0.65 and a sill of 1.25 (all semi-variogram values normalized by the variance of the dataset). 1 foot = 0.3 m.

***Seasonality and long-term variations.*** Spatially averaged mean N concentrations vary significantly over time although the 4-year observation period (1995-1999) is too short to detect significant long-term trends. Seasonal influences in source strength (irrigation during the summer, fall and winter land application of manure, winter rainfall) are not reflected in the temporal changes in groundwater nitrate: Average N during the four seasons Sep-Nov (fall), Dec-Feb (winter), Mar-May (spring), Jun-Aug (summer, main irrigation season) varies little. A time series

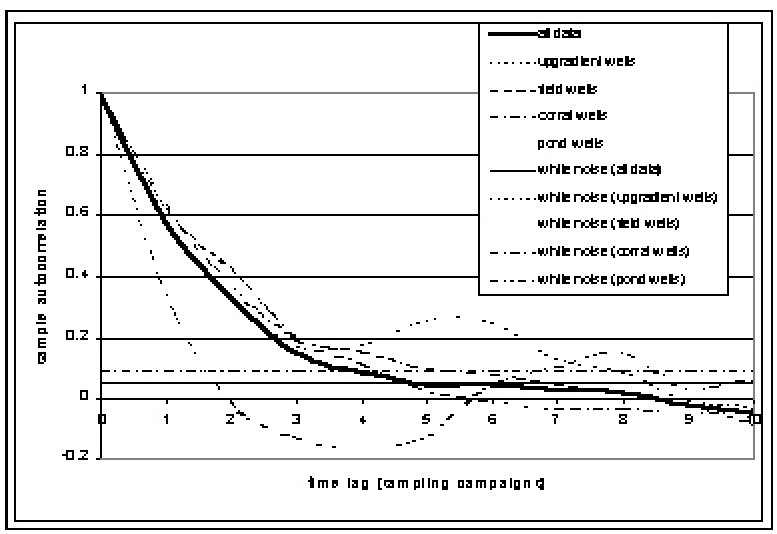


**Figure 4**: Sample autocorrelations in time for the complete dataset (solid line) and for individual management units. Estimated white noise levels are represented by the corresponding horizontal lines. Significant correlation exists only above white noise levels.

analysis was performed for thirty-five sampling dates between November 1995 and November 1999. For the analysis, each sampling interval was given a duration of 1. The actual sampling intervals varied from 27 days to 74 days with an average of 43 days. The sample autocorrelations of the total dataset, the upgradient wells, the field wells, and the corral wells are very similar. The time lag at which the autocorrelation decays to that of a white noise process is approximately 4.5, corresponding to a real time lag of approximately 190 days (6 months). The mean absolute difference of N between individual sampling dates is slightly above 10 mg/l for the total sample and for the field wells. It increases to 15 mg/l at time intervals of 2 lags (86 days). Pond wells show the largest variability between sampling campaigns and much shorter correlation time than the remaining wells (Fig. 4).

***Implications for groundwater monitoring***. The large amount of spatial and temporal variability raises the question of how to effectively monitor AFOs. We discuss four hypothetical approaches to monitoring. The discussion is preliminary and currently subject to further data review.

1. *Characterization of the impact of individual potential sources within a dairy on groundwater quality*. Individual potential sources within a dairy are, for example, a wastewater pond, an individually managed field, or continually ponding local areas ("hot spots") within a corral. The impact of individual sources can either be estimated from the leaching rate if known (e.g., net recharge in irrigated fields) or - in the case of a field - the nitrogen imbalance between fertilizer and manure applications and crop N uptake. These data can be used by computer models to estimate long-term impacts on shallow or deep groundwater, an approach that we have successfully applied to predict impacts from improved manure management. For many potential sources (ponds, corrals, leaking pipelines) neither the leaching rate nor the leaching concentrations are known. We are pessimistic that individual sources can be isolated and characterized by monitoring shallow groundwater concentrations. We are currently evaluating the use of other geochemical signatures to achieve better source identification.

2. *Characterization of the detailed spatial (and temporal) distribution of nitrate to map potential hotspots*. If areas with extremely high concentrations of nitrate are discovered, they are likely to be of limited spatial extent. The exact size of the associated plume can only be determined by installing closely spaced monitoring wells (distances between wells of 30 m or less). Such dense monitoring well systems are currently found only on industrial groundwater contamination sites. Other than for research purposes, this approach does not seem economically feasible for most AFO operations. Clear groundwater protection goals must be established prior to designing such networks and weighed against the high cost of installing a dense monitoring well network within a small portion of the AFO.

3. *Estimation of the overall nitrate loading rate to the water table within the dairy*. For practical purposes, our measured N distribution can be approximated reasonably well by the Gaussian probability distribution. If a sparse monitoring well network is installed with individual wells separated by at least one to a few hundred meters, the individual well samples are independent of each other. Gaussian mean error estimation can then be applied to determine the number of wells necessary to obtain a reasonable estimate of the mean shallow groundwater nitrate concentration across an AFO. We have found that the average nitrate concentration from six to seven monitoring wells within a dairy (and distributed across all management units) are within 10% - 20% of the nitrate concentration observed in the outflow from a tile drain system underlying the entire AFO (including crop fields).

Alternatively, total farm N budgets based on the number of animals, the type of crop, water use, and the crop area of a farm have been used to estimate overall nitrate loading to groundwater. Such budgets are an important tool for planning and regulatory compliance purposes. The farm budgets for the five participating dairies indeed all showed an N surplus. However, no correlation exists between the farm N surplus and actual groundwater nitrate. While mean groundwater nitrate varied little between the dairies, their annual farm N budgets showed surpluses ranging from as little as 60 kg/ha to over 400 kg/ha (60, 95, 260, 300, and 420 kg/ha; Davis, *personnal communication*). Farm N budgets were computed based on handbook values (rather than measured values) for animal N excretion, N content of liquid and solid manure, and N uptake from farm crops. It is our experience that actual values for these parameters may vary significantly from farm to farm depending on feed management, manure handling, and irrigation system (e.g., Harter et al., 2001b, Mathews et al., 2001). Additional uncertainty is introduced by non-uniform manure and irrigation water applications within each field.

The use of farm N budgets for assessing groundwater loading is also limited by the scale of the N throughput in these dairy farms (on the order of 1,000 kg/ha) compared to the amount of surplus N that would result in recharge nitrate-N concentrations exceeding 10 mg/l. At a net recharge rate of 30 cm/year, that concentration results from as little as 30 kg/ha annual N surplus, which is much less than the margin of error of a typical farm N budget. Better estimates of groundwater N loading are obtained from individual field nitrogen balances based on actual (measured) N applications to the field and actual (measured) N uptake in the crop (Harter et al., 2001b).

4. *Monitoring to determine, whether any significant nitrate impact to groundwater exists at all within the AFO*. Depending on the definition of 'significant impact', this type of monitoring, as an early warning system, would require the least amount of monitoring wells. Let's assume that the true average nitrate concentration in the shallow-most groundwater across an AFO is $N_{mean}$ and that the spatial distribution of nitrate in shallow groundwater under an AFO follows a Gaussian distribution. Then the likelihood, $p$, that all $n$ monitoring wells in a network have levels that are less than $N_{mean}$ is: $p = 0.5^n$. Generally, for an arbitrary distribution with a known cumulative distribution function of nitrate, CDF(N), we can compute $p$ (the probability that all $n$ wells return levels less than $N_{mean}$) from:

$$p = [\mathrm{CDF}(N_{mean})]^n \tag{1}$$

This assumes that concentrations are uncorrelated between wells. At our study site, the separation distance between wells would have to be on the order of 100 m or more to meet that requirement. To design a monitoring well network such that at least one well, with 95% certainty, has a nitrate concentration equal to or larger than $N_{mean}$ means that the well network needs to contain $n$ wells such that $(1- p) > 0.95$. Based on our exhaustive sample CDF of nitrate, we estimate from (1) that $n = 4$. If nitrate samples are normal (Gaussian) distributed, $n = 5$. In practice, these $n$ wells should be located in areas that are most likely to leach nitrate. The wells should be sampled at least quarterly to half-yearly to avoid missing any intermittent periods of high N concentrations in the well. As long as none of these wells exceed a predefined threshold level, it can be assumed with reasonable certainty that overall groundwater nitrate impact from the AFO area does not exceed the threshold level.

We emphasize that such recommendations apply only to the shallow-most groundwater under the direct influence of the AFO (regardless of its depth). Monitoring the shallow-most groundwater (i.e., the upper 5-10 m immediately below the water table) is only possible in areas with relatively stable water levels. Where seasonal or long-term water table fluctuations exceed 10 m, monitoring wells must be screened over larger depth intervals resulting in depth-averaging of nitrate concentrations. The potential source area of such wells changes over time (as water levels rise and fall) and may include significant land outside the farm of interest. This must be taken into consideration when interpreting data from these monitoring wells.


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