COW NUMBERS AND WATER QUALITY – IS THERE A MAGIC LIMIT? A GROUNDWATER PERSPECTIVE

Thomas Harter[1] and John Menke[2]

When dairy operators talk to regulators about water quality, a common question is "how many cows can be at the dairy?" Before replying, the regulator may ask about the types of cows, available cropland, cropping program, manure application practices, and other facility characteristics. The regulator may then apply a 'rule' such as "five milk cows produce enough nitrogen to fertilize one acre that is double cropped" and provide an answer. However, both operators and regulators are learning that there are many additional issues including air quality, animal health, and food safety that need to be considered. In this paper, we consider the question of "how many cows?" by focusing primarily on groundwater quality issues related to manure management on dairies.

More cows means more animal waste, and more animal waste is generally perceived to mean an increased risk of water pollution. Is that indeed the case and, if so, how can that risk be minimized? To answer those questions, we need to understand the evolving legal framework related to dairies, what constitutes water pollution, how the nutrient and salt balance on dairies affects the potential for groundwater pollution, and what source management and monitoring efforts can reduce the threat to water quality.

Other animal farming operations than dairies, the food processing industry, and many urban areas also create and land apply significant amounts of manure, food processing waste, or biosolids. While specifically written with dairies in mind, the framework set out in this article similarly applies to these latter kind of land applications.

WATER POLLUTION: LEGAL FRAMEWORK

Until the late 1960s, there was little regulatory enforcement of pollutant discharges into either surface water (streams, rivers, and lakes) or groundwater. In California, the Porter-Cologne Act of 1969 (part of the "Water Code") established the State Water Resources Control Board (SWRCB) and nine Regional Water Quality Control Boards (RWQCBs) as the regulatory agencies primarily responsible for addressing water quality issues in the state. The RWQCB boundaries correspond to the large watersheds ("basins") in California, and each RWQCB prepares a "Basin Plan" that describes the quality of surface water and aquifers within the basin. The Basin Plan also identifies existing or potential water quality problems in the basin and establishes water-quality goals. The Water Code and the Basin Plans provide the regulatory authority and framework within which the RWQCBs and SWRCB protect water quality. The associated regulations are in Titles 23 and 27 of the California Code of Regulations (CCR). Pursuant to the CCR, anyone who discharge wastes (i.e., "a discharger") must obtain Waste Discharge Requirements (WDRs) from the appropriate RWQCB. However, the RWQCB can waive the need for WDRs if certain conditions are met.

In 1972, Congress passed the Clean Water Act (CWA) that regulates direct pollutant discharges into surface water as well as activities that indirectly affect surface water quality through groundwater that

[1] Associate Cooperative Extension Specialist, Department of Land, Air, and Water Resources, University of California, Davis, CA 95616. ThHarter@ucdavis.edu. For additional information and related publications, visit http://groundwater.ucdavis.edu. Revised version (January 2005) of a manuscript published as: Harter, T., Cow numbers and water quality – is there a magic limit? A groundwater perspective; In: Proceedings, National Alfalfa Symposium, 13-15 December 2004, San Diego, CA; UC Cooperative Extension, University of California, Davis 95616. (See http://alfalfa.ucdavis.edu for this and other proceedings).
[2] Environmental Scientist, California State Water Resources Control Board, Division of Water Quality, Sacramento.

enters surface water. In California, the provisions of the CWA were incorporated into the Water Code. During the first thirty years after adoption of the CWA, most of the associated regulatory efforts focused on controlling point-source discharges of pollutants into surface water (for example, discharge from municipal wastewater treatment plants and industrial processing facilities). Each point-source discharger must apply for a National Pollutant Discharge Elimination System (NPDES) permit that defines the level of wastewater treatment and the monitoring requirements that the discharger must implement.

Although the CWA is focused on surface water quality, the Water Code also includes provisions for protecting groundwater. Groundwater quality objectives are defined in the individual Basin Plans. All Basin Plans require that land-use activities and waste discharges that may impact groundwater quality be managed to prevent groundwater degradation at levels that impact the "beneficial uses" of groundwater. Beneficial uses of groundwater throughout most of California include domestic, municipal, and agricultural supply.

Pursuant to the CWA, the Water Code, and the CCR, dairy operators are prohibited from discharging animal waste into surface water or groundwater. In 1974, the CCR was changed to require dairy operators in California to ensure that wastewater ponds were underlain with soil containing at least 10% clay or lined with equivalent material. To meet storage requirements, the pond capacity needs to be adequate to contain rainfall from the largest 24- hour storm that would likely occur over a 25-year time-span as well as all the wastewater (washwater and stormwater runoff from manured areas) produced between the intervals when wastewater could be applied to cropland. The CCR also requires dairies to apply manure and wastewater to cropland at rates that are "reasonable for the crop, soil, climate, special local situations, management system, and type of manure." As long as an operator appeared to comply with the CCR, the need to obtain WDRs was waived for most dairies, and no reporting or monitoring was required. In most parts of the state, no state permit was needed to construct a new dairy or to construct a new pond at an existing dairy.

In contrast to WDRs issued to dairies, NPDES permits for other types of dischargers specify waste treatment practices, pollutant discharge limits, and monitoring requirements. However, despite the limitations imposed under NPDES permits, water quality objectives have not been achieved in many watersheds, often due to unregulated sediment and nutrient discharges from non-point sources, such as agricultural runoff. In response, the portions of the CWA that deal with non-point sources have recently received increased attention. "Total Maximum Daily Load" (TMDL) limits are now being enforced in watersheds with continued water quality degradation in surface waters. The TMDL process is believed to be a better way to control discharges from non-point sources and is compatible with a watershed-based approach to manage both point sources and non-point sources. In many watersheds, groups have formed to coordinate the implementation of improved land-management practices and required water-quality monitoring.

Until January 2003, application of nutrients and irrigation water to cropland was categorically exempt from permitting requirements in California except that certain pesticide application and management practices were required by the California Department of Pesticide Regulations as part of a groundwater protection program. In 2003, agricultural runoff into surface lost its categorical exemption and became a regulated waste discharge subject to state regulations. Requirements for all runoff from agricultural lands to surface waters are currently being put in place through an "agricultural discharge waiver program." The new program affects all growers with land that drains to surface water. The current program is specifically focused on surface water but may be expanded in the future to address groundwater.

Also in 2003, new federal regulations broadened the scope of NPDES permitting to specifically include concentrated animal feeding operations (CAFOs). CAFOs are animal farming facilities with animal populations above specified numbers. Under the new regulations, CAFOs, including associated cropland that receives animal waste, are now defined as “point sources” and must apply for a NPDES permit. In California, dairies with 700 or more adult cows are the primary CAFOs.

In California, CAFOs will not only have to comply with requirements to protect surface water (the main goal of the federal NPDES program), but also with provisions in the CCR and Basin Plans that address groundwater protection. The Central Valley RWQCB has released an administrative draft version of a combined NPDES permit and Waste Discharge Requirements order (“permit and order”) that will apply to approximately 1,000 of the 1,700 dairies in the Central Valley. In addition, the Santa Ana RWQCB has released a draft permit and order that updates the existing permit and order that applies to the approximately 250 dairies in the region, most of which are in the Chino Basin. Because the Chino Basin has significant groundwater contamination resulting from historical dairy operations, the permit and order applies to all dairies over 50 adult cows and prohibits land application of manure within the region.

For dairies in the Central Valley, the new permit and order is the first major change in the regulatory framework since the adoption of applicable regulations in the CCR in 1974. Under the proposed permit and order, each dairy would be required to develop and implement a waste management plan (WMP) for the production area (corral, pond, feed and solid waste storage areas) and a nutrient management plan (NMP) for the land application area. The plans must be prepared and certified by recognized professionals. Dairies may also be required to install groundwater-monitoring wells to demonstrate that groundwater quality goals are achieved and to file annual reports to document implementation of the plans and performance of the required monitoring.

What are the groundwater quality goals of California’s Basin Plans? They are descriptions of the existing and potential beneficial use of the aquifer. Waste management practices that would adversely impact beneficial uses are considered undesirable. Because domestic and municipal supply generally have the most restrictive requirements, the goals are primarily driven by standards that apply to drinking water. Historically, nitrate and salinity have been the primary potential groundwater pollutants of concern at dairies, although pathogens may be a concern in some areas.

POTENTIAL WATER POLLUTION SOURCES IN DAIRIES

A typical NPDES permittee is a discharger with a single piped or channeled discharge to surface water. A dairy is a significantly larger and more complex potential pollution source than most NPDES permittees because the typical dairy has land application areas that measure from several hundred to several thousand acres. With respect to groundwater, there are no specific “discharge locations.” The entire dairy and its associated crop land may be considered a spatially continuous if heterogeneous source of potential pollutants. In addition, typical “point-sources” such as dry cleaners, gas stations, industrial spill-sites, and food waste generators have a history of regulation that can be used to identify waste management practices that are protective of water quality. No such history is available for dairies.

For purposes of characterizing the potential impact on groundwater quality, a dairy can be divided into several “management units”: the animal housing area (corrals and free-stall barns), the milking barn, wastewater storage ponds, solid manure processing and storage area, feed storage areas, and the fields that receive either wastewater or solid manure or both. Each of these management units is a potential groundwater pollution source. Furthermore, the groundwater recharge process, including chemical reactions during recharge, can be significantly different between these management units.

The milking barn is usually a paved area with little or no infiltration; most corrals are earthen surfaces with a compaction layer but no liner; wastewater storage ponds may meet the 10% clay requirement plus have a dense mat of organic debris, but still have some seepage. Fields that receive manure must have good drainage to achieve reasonable crop yields, hence they can be a source of waste constituents that move to groundwater.

Even within an individual management unit, there is potentially significant spatial variability in the pollutant loading and groundwater recharge process. Certain areas of the corrals are preferably used by animals and will have higher waste loading. Some areas of the corral are more likely to have standing water and hence increased waste infiltration. The manure application to fields can be non-uniform due to incomplete mixing of wastewater and other irrigation water, or due to variable soil conditions. Nutrient uptake can vary in different areas within a field. As a result of these varying conditions, some areas at a dairy may contribute larger amounts of nitrate to groundwater recharge than others (Harter et al., 2003). The potential variability in salinity and nitrate groundwater loading rates across a dairy is a challenge both from a waste and nutrient management point of view and with respect to monitoring the effectiveness of waste and nutrient management to protect groundwater.

EVALUATING THE THREAT OF GROUNDWATER POLLUTION: NUTRIENT AND SALT BALANCES

The most important tools for evaluating the potential nitrogen and salt losses to groundwater are nutrient and salt mass balances for the farm as a whole and for individual fields that receive manure solids or wastewater. Preparing the nitrogen or salt mass balance is like balancing a checking account. At the farm level, the "account" is the amount of nitrogen or salt available on the farm as a whole at any given time. At the field level, the "account" is the amount of nitrogen or salt stored in the root zone of the field at any given time; the process can be represented as:

INPUT – OUTPUT – LOSSES = CHANGE IN ACCOUNT BALANCE

For salts, there are neither volatilization losses nor losses due to transformations such as denitrification. Also, most salts at a dairy are relatively unlikely to bind to soil, hence the salt losses computed from the whole farm salt mass balance all go towards groundwater loading.

For nitrogen, because nutrient discharges to surface water losses are prohibited, they can be neglected. Therefore, the focus is on losses to the atmosphere, to groundwater, and to attenuation (i.e., to storage and denitrification in the soil). For example, for a whole-farm mass balance, the nitrogen (N) account looks like this:

Whole-Farm Mass Balance:

INPUTS = purchased feed N + commercial fertilizer N + irrigation water N + atmospheric deposition N

OUTPUTS = milk sales N + solid manure export N + animal growth/sales N

LOSSES = volatilization of ammonia-N + denitrification of nitrate-N + groundwater loading of nitrate-N

For nitrogen and salts, the inputs and outputs can be calculated using farm records. Atmospheric deposition of nitrogen is relatively small and adequately known from the literature. Similarly, animal growth and animal sales contribute only little to the overall farm nitrogen balance, unless there are significant changes in farm size. On the other hand, the losses are all difficult to measure. How do we know how large the losses are and how much of it is in the "nitrate-N to groundwater" category?

The estimation of losses can be done by making a long-term assessment. Over the course of one or more years, the total amount of salts and nitrogen stored at a dairy in form of feed, manure, and retention in soil is in a quasi-equilibrium. This is much like someone's checking account that always runs around $1000 even though there may be quite a change in the account balance between the beginning of the month and the end of the month. At the end of the year (hopefully), there is still about $1000 in the account. Hence, over a long term (e.g., annually), there is a negligible change in the account balance. This is called a "quasi-steady-state" mass balance and is represented by the following equation:

Annually: INPUT – OUTPUT – LOSSES = 0

If we can measure all the inputs to the account and all the outputs from the account, the losses from the account are determined by taking the difference between inputs and outputs as shown by the following equation:

Annually: LOSSES = INPUT - OUTPUT

Once we have determined the nitrogen losses using this mass balance method, we can estimate volatilization and denitrification losses from literature values and then obtain the groundwater nitrogen losses by subtraction as follows:

Annually: Nitrate-N to groundwater = LOSSES – ammonia-N volatilization – denitrification

Because of the uncertainties about the exact amount of ammonia-N volatilization and denitrification, this is not a precise method, but it is a tool that will indicate if a farm is grossly out of balance with respect to nitrogen. The largest unknown in the above procedure is the amount of nitrogen volatilization in the animal production and manure storage areas prior to land application. A field-by-field mass balance circumvents this issue by focusing on nitrogen that is actually applied to each field. Also, a field-by-field assessment takes into account differences in the management of individual fields. For a field, the nitrogen mass balance, the inputs and outputs are:

Field Mass Balance:

INPUTS: solid and liquid manure N + commercial fertilizer N + irrigation water N + atmospheric deposition N

OUTPUTS: crop harvest N

The losses are the same as on the farm level (volatilization, denitrification, and nitrate loading to groundwater). However, since much of the ammonia volatilization occurs prior to the application of manure to the field, the uncertainty about the volatilization losses is significantly smaller. To obtain a field mass balance, detailed records of the amount of irrigation water and manure applied are needed along with analyses of the nitrogen content in the individual manure applications. Currently, collection of this data is occurring at only a few dairies, but collection of such data will likely become routine at all dairies that must comply with the NPDES permit in the Central Valley Region.

UNDERSTANDING NUTRIENT BALANCING, PART 1: CURRENT CONDITIONS

In a recent research project, we found that a typical field nitrogen mass balance prior to targeted nutrient management may look like this (numbers are approximate pounds of nitrogen per acre per year):

INPUTS	Commercial fertilizer N	250
	Liquid manure, organic N	450
	Liquid manure, ammonia N	350
	Atmospheric deposition	10
	Irrigation water N	10
	Total Inputs	**1070**
OUTPUTS	Crop removal – summer corn	300
	Crop removal – winter grain	200
	Total Outputs	**500**
LOSSES	**Total Losses (= Total Inputs – Total Outputs)**	**570**
	Volatilization (less than 10% of applied N)	0-100
	Denitrification (less than 10% of applied N	0-100
	Groundwater Nitrate-N loading (= Total Losses – Volatilization – Denitrification)	**370 – 570**

Table 1: Typical nutrient mass balance in a field that receives from four to six diluted liquid manure applications each year, typically during spring, and also receives pre-irrigations in the fall and pond releases in the winter in order to maintain storage capacity for stormwater.

How good or bad are groundwater nitrate-N loading rates that are on the order of 370 to 570 pounds of nitrogen per acre? To find an answer, recall that most groundwater in the Central Valley has “drinking water” designated as one of its beneficial uses. The drinking water limit for nitrate-N is 10 mg/l. The amount of nitrogen in 1 acre-foot of water at the drinking water limit is 27 pounds. Typically, annual groundwater recharge rates underneath irrigated forage crops range from 1 to 2 acre-feet per acre (assuming irrigation efficiencies between 70% and 50%). Hence, average losses of nitrate-N to groundwater should be no more than approximately 27 to 54 pounds per acre per year after accounting for volatilization and denitrification. This amount is about one-tenth of the amount available for leaching to groundwater in the example above!

The above example shows that without nutrient management, actual nitrate-N losses to groundwater can be an order of magnitude higher than desirable, resulting in significant groundwater degradation. Indeed, we commonly find shallow groundwater nitrate-N concentrations of 50 to over 100 mg/l underneath fields with frequent applications of liquid manure – that is 5 to 10 times above the drinking water limit. We recently determined that the average nitrate-N concentration in shallow groundwater recharged from fields with manure applications in the Hilmar-Modesto region averaged over 60 mg N/l (Harter et al., 2002). Similar average concentrations of total nitrogen were found in recharge from corrals and storage ponds.

Because fields comprise 80 to 90 percent of the land area of a dairy, more efficient utilization of the manure as a fertilizer and a corresponding reduction of the nutrient and salt load in the cropland area is the key to addressing groundwater quality issues on dairies. This is not to say that improvements to waste containment are also needed in the corral and pond management areas of the dairy, particularly as the size of ponds is likely to increase as a result of increased nutrient management. However, the largest potential reduction in groundwater impacts is currently associated with improvements in waste application to cropland.

Mathews (2004) presented the results of a research project where nutrient management was implemented using frequent flow metering and field-testing of manure nitrogen content. Significant reductions were achieved on the input side of the field mass balance in Table 1 by eliminating the use of commercial fertilizer, reducing manure applications, and making manure applications only during crop growth stages. There were no significant reductions on the output side (no crop yield losses) associated with the changes. As a result, groundwater quality underneath the research field improved substantially (over 70% improvement). It is important to note that significant adjustments in the infrastructure and management of existing facilities are generally necessary to properly implement the improved nutrient management practices (Campbell-Mathews et al., 2001).

Whole-farm and field-by-field nitrogen and salt mass balances are effective tools to check for large nitrogen and salt imbalances that pose an unacceptable risk for groundwater degradation. Where field nitrogen inputs exceed field nitrogen outputs by several hundred pounds of nitrogen per acre, as in the example above, groundwater contamination is an almost inevitable consequence, unless there are strong nitrate-reducing conditions in the subsurface above or at the water level.

The amount of volatilization and denitrification losses that may occur under specific soil and geologic conditions is difficult to estimate. In some areas, denitrification losses below the root zone may degrade significant amounts of nitrate before it enters groundwater; however, the occurrence of conditions that favor denitrification must be evaluated locally. We currently have little knowledge about the exact denitrification potential in the deeper unsaturated sediments of the eastern Central Valley dairy regions. However, due to relatively good drainage and other geologic conditions in this region, denitrification is unlikely to occur on the order of hundreds of pounds of nitrogen per acre each year. Our assessment of monitoring data in the Hilmar-Modesto area indicates that denitrification in that region does not account for significant losses in light of the overall imbalance between inputs and outputs in that region.

UNDERSTANDING NUTRIENT BALANCING PART 2: HIGH RISK AREAS

With respect to cropland where animal wastes are utilized, high-risk areas are where total nutrient inputs from animal wastes are high. That is because the uncertainty about the mass losses of nitrogen from volatilization and denitrification increases proportionally with the total animal waste inputs to a field.

Ideally, when nutrient management practices are in place and inputs and outputs are balanced, volatilization and denitrification rates are of approximately the same magnitude as the difference between inputs and outputs. However, as long as significant uncertainty exists about volatilization and denitrification losses, groundwater protection is not guaranteed. Reasonable estimates of volatilization and denitrification losses for conditions typical of dairy areas in the eastern San Joaquin Valley and Tulare Lake basin range from 5 to 40 percent of total inputs; that is from a few tens to a few hundreds of pounds of nitrogen per acre per year. In other words, the uncertainty about these losses is often much larger than the targeted maximum loss of nitrate to groundwater.

If a dairy operator intends to achieve corn and winter forage crop yields equivalent to an output (i.e., uptake) of 600 pounds of nitrogen per acre per year and is uncertain if the volatilization and denitrification losses of nitrogen in the root zone are 30 to 240 pounds per acre per year (based on the 5 to 40 percent uncertainty), how much nitrogen should be applied? To ensure good crop yields, (s)he would apply 600 + 240 = 840 pounds of nitrogen per acre per year. But if it turned out at the end of the year that volatilization and denitrification losses totaled only 50 pounds of nitrogen per acre per year, the remaining 190 pounds of nitrogen per acre per year will leach into groundwater resulting in significant groundwater degradation (recall that the target for nitrogen loss to groundwater is 27 to 54 pounds of nitrogen per acre per year).

The problem of accounting for volatilization and denitrification losses is not unique to cropland at dairies, but is an underlying issue in nutrient management of other agricultural systems as well. However, many dairies in California stand out relative to other farming operations due to the intensive farming practices needed to utilize the large quantities of available nutrients and the high percentage of organic nitrogen that is applied. As with vegetables and other crops that require application of large quantities of nutrients, the uncertainties about nitrogen losses results in significantly higher risks for groundwater contamination. The increased risk occurs as a result of the large nutrient throughput in forage crops. Large nutrient throughput may be practiced regardless of dairy size. The higher risk is therefore not necessarily a function of the dairy herd size.

UNDERSTANDING NUTRIENT BALANCING, PART 3: THE RISKS OF ORGANIC FARMING ON A DAIRY

Dairies and organic farms utilize large amounts of organic nitrogen in their cropping systems. Unlike nitrogen in ammonia, urea, and nitrate, the organic nitrogen in manure is a complex mix of compounds, some of which will mineralize to plant-available ammonia-N and nitrate-N very quickly, and some of which will mineralize very slowly. Significant uncertainty is associated with predicting the rate at which organic nitrogen in manure will become plant-available. Effectively, a significant portion of the organic N in manure will act as a slow-release fertilizer that may release nitrogen at significant levels throughout the year. These slow-release dynamics are ill-matched with the large, fast, and short-lived nutrient uptake dynamics of many high-yielding feed cropping systems: the main uptake for a double-cropped corn/winter grain system is in June/July and in February/March. Nutrient requirements during the remaining year are relatively small.

Hence, the ability to properly balance inputs and outputs in a field is significantly hampered where large amounts of organic nitrogen (several hundred pounds per acre per year) are part of the inputs. Organic farmers share this problem with dairy operators but with one significant difference: the total inputs and outputs of nitrogen in organic farming systems are typically much lower due to lower yields - and therefore the risk for excessive nitrogen losses to groundwater is much lower.

UNDERSTANDING NUTRIENT BALANCING, PART 4: BOTTOM-LINE

This brings us back to the original question: how many cows can be at a particular dairy? From a groundwater perspective the answer appears simple: the number of cows that will not cause groundwater to be degraded (the number may be different from an air quality perspective). However, that simple answer does not provide a dairy operator with useful information.

If the goal is to keep nitrate-N losses to groundwater less than 27 to 54 pounds per acre per year as previously mentioned, we need to increase our knowledge about organic-N mineralization rates, volatilization losses, and denitrification losses. Increased knowledge will come from research data and will allow development of appropriate management practices. However, farmers that depend solely on manure to supply needed nutrients may be subject to some limitations, particularly with respect to the use of the organic-N portion as “fertilizer.” Until it is possible to predict the availability of organic-N in manure it will not be possible to eliminate a potentially significant loss of nitrogen from cropland where manure is applied.

One approach that has been used to increase the “number of cows per acre” is to increase the crop production per acre and thereby increase the nitrogen uptake per acre. Such a remedy has been proposed in recent dairy EIRs (Environmental Impact Reviews), which seek to maximize the number of cows on the available land. However, without a corresponding decrease in nitrogen losses, this approach only increases the total nitrogen that can move from cropland to groundwater.

The total number of cows at a dairy could be increased if the dairy exports manure as a soil amendment, fertilizer, or other “product.” There is ample room for creative solutions. However, salts present in the manure are not degraded or volatilized by composting or similar treatment. Hence, even after balancing nutrients, salts will be able to leach to groundwater. Salt loading may ultimately become the limiting factor, not only in closed groundwater basins such as the southern part of the San Joaquin Valley (the Tulare Lake Basin), but in other areas where subsurface drainage is not captured and exported from the basin.

EVALUATING AND MONITORING THE THREAT TO GROUNDWATER AT DAIRIES

The most important steps for evaluating the threat to groundwater posed by a dairy are to conduct an annual whole-farm nitrogen and salt balance and then to determine field-by-field nitrogen and salt mass balances. These will indicate if a facility is grossly out of balance or within some acceptable range. Where the facility is grossly out of balance (for example, field balances where nitrogen inputs are twice outputs), groundwater pollution is highly likely unless mitigating factors such as a high rate of denitrification are present.

Soil and plant tissue sampling is also an important tool for managing irrigation and nutrient applications on dairies. Because of uncertainties about mineralization of organic-N, such testing is an important tool to ensure adequate crop yields without excessive applications of nutrients.

When mass balances identify facilities with a high potential for groundwater impacts, actions can be taken to reduce the threat to water quality. Such steps are usually to export solid manure to another location, to acquire additional land for wastewater application, or to switch to crops that have higher nitrogen uptake. However, given that nitrogen outputs from cropland at dairies will continue to be high (400 – 600 pounds of nitrogen per acre per year) relative to the acceptable nitrogen losses to groundwater (27 – 54 pounds of nitrate-N per acre per year), and considering current uncertainties about volatilization and denitrification and the vagaries of managing large amounts of organic nitrogen, neither whole-farm or field-by-field nutrient and salt balances nor soil sampling will provide an absolute guarantee that groundwater is protected – at least until a significant amount of research and on-the-ground experience will significantly reduce that uncertainty.

Groundwater monitoring at the water table, where recharge water from the dairy can be directly measured, is the only way to directly assess groundwater quality impacts from dairies. However, groundwater monitoring also has significant uncertainties for making an assessment of the overall groundwater nitrate and salinity contribution from a dairy. A groundwater monitoring well measures recharge water quality from only a small amount of land within the dairy (and, under some circumstances, beyond the dairy). In light of the large spatial variability in the nitrate and salt loading rates across the dairy, the question arises, how many wells it would take to allow for an adequate assessment of the groundwater quality impacts from a dairy facility (corrals, ponds, storage areas, and fields)? We explored this question by analyzing nitrate and salt data from monitoring well networks with 8 to 25 monitoring wells per dairy on five dairies, and compared data to those collected from tile-drains that drained entire dairy facilities (Harter et al., 2003). Average concentrations of nitrate in one to two dozen monitoring wells per facility (across all management units) were found to be comparable to those from the tile-drain network, which is presumably the best indicator for whole-farm impact on groundwater quality.

But is it practical and necessary to install that many monitoring wells on each dairy facility? Based on statistical analysis of our dataset, we have argued that 4-6 wells, located down gradient from the highest risk areas within a dairy, is sufficient to determine whether or not the dairy has a potential to significantly impact groundwater. The areas of primary concern are corrals, ponds, and fields with high manure loading rates and high-risk characteristics such as shallow groundwater, coarse soils, and underlying conduits such as gravel channels. If none of the wells exceed water quality objectives, the facility as a whole can be assumed with high certainty to not be detrimental to groundwater quality. If the majority of the wells indicate water quality problems, the facility is likely out of compliance. However, when just one well indicates a water quality problem, the interpretation of data from such a small network of wells is problematic. Such situations generally force installation of additional monitoring wells to aid the assessment.

Other monitoring activities may be an acceptable alternative that in some cases may be superior to groundwater monitoring. When groundwater is deep and/or is overlain by aquitards, it may take a long time for pollutants to reach groundwater. Vadoze zone monitoring or soil monitoring may be a considered as part of an initial monitoring program at such sites because it can detect potential groundwater impacts before they occur. However, such sampling programs require large amounts of sampling sites due to the significant spatial variability in soil and deep vadose zone nitrogen concentrations (Onsoy et al., 2004).

Focused studies at representative dairies may also result in enhanced groundwater protection without monitoring groundwater at all dairies. Such studies may utilize many more wells than conventional groundwater monitoring and result in better understanding of the mechanism of pollutant movement and the response to various control strategies. Desired improvements in waste management practices can then be required at dairies that have characteristics similar to the study site. Regional monitoring programs may also provide needed information at less cost to operators and to regulatory agencies that must review monitoring data. Such monitoring is discussed in the following section.

GROUNDWATER MONITORING AS A REGULATORY TOOL

The draft permit and order issued by the Central Valley RWQCB for CAFOs that are dairies requires groundwater monitoring at the facilities. This is the first time that a regulatory agency has proposed requiring production agriculture to use groundwater monitoring as part of normal operations. No other agricultural enterprise has, to date, been subject to such a requirement, although some production regions with high levels of fertilizer use, such as the Salinas Valley, have significantly stepped up education and regional monitoring efforts through local agencies (e.g., the Monterey County Water Resources Agency).

Monitoring groundwater quality at agricultural lands as point source adds different dimensions to typical point source monitoring. The most significant differences are land size and source size. A gas station or dry cleaner site typically has a single pollutant source and is limited in size to an acre or less. Even a large point source discharge such as from a food processor typically involves a few tens to one hundred acres. In contrast, California's CAFO dairies each occupy several hundred to a few thousand acres of land, all of which are potential sources of groundwater contamination. A monitoring program that thoroughly scans discharges across the entire application area would be unprecedented. Such a monitoring program is not intended by currently proposed regulations due to its economic impacts and strong resistance by the dairy industry to excessive regulatory requirements.

The draft permit and order imposes groundwater monitoring on dairies in a sequential hierarchy based on number of cows. However, the number of cows alone does not directly relate to the threat to groundwater quality. Groundwater monitoring should first be focused on facilities located in areas where the potential for groundwater impacts is higher and on facilities that have other characteristics indicative of an increased threat to groundwater. The following characteristics should be considered:

- Ratio of nutrients to crop needs (e.g., "ratio of cows to acres")
- Current land application practices
- Depth to groundwater
- Soil characteristics
- Geologic setting.

Groundwater monitoring is only a secondary tool and should be used only after mass balance computations have been made. Where mass-balances indicate large amounts of nitrogen leaching, a presumption of adverse groundwater impact could reasonably be made without first installing groundwater monitoring wells, particularly in hydrogeologic areas considered to be vulnerable to nitrate contamination and known to have limited denitrification potential (this includes much of the eastern San Joaquin Valley).

Unfortunately, the reverse option does not work: where mass-balances are adequate, a presumption of negligible threat to groundwater cannot be made a priori, as discussed above. But opportunity exists for the design of regional monitoring networks with only a limited number of monitoring wells per dairy facility (Harter et al., 2003). The regional network would not be designed to evaluate each discharge of manure to cropland; rather, it would ensure that the overall impact of dairy facilities within a region is not detrimental to groundwater. The groundwater monitoring network would be designed to minimize the number of monitoring wells needed per facility while providing a sufficiently accurate spot-check of groundwater quality.

A key to the continued success of dairying may be that sufficient (but not intensive) groundwater monitoring is implemented at key locations across multiple facilities that share similar hydrogeologic, pedologic, and agronomic management practices. The purpose of such a monitoring network must be to identify and quickly address problematic management practices utilized at these facilities as early as possible (Harter et al., 2003). Such groundwater monitoring would be part of a suite of monitoring tools. A complete monitoring program would primarily rely on accurate reporting of annual farm and field-by-field nutrient and salt mass balances.

LONG-TERM OUTLOOK

Groundwater impacts from farming activities at dairies can be minimized by ensuring that best available practices are used for nutrient applications. Such practices will necessitate that dairy operators have the ability to control the rate of manure and wastewater applications to cropland and the ability to determine the nitrogen content in the material applied. Operators will also need to apply nutrients at appropriate times and maintain accurate records on crop yields and nutrient uptake relative to the nutrients applied. If operators have an annual program to reduce nutrient applications (including organic-N) to the minimum needed for acceptable yields, the impacts to groundwater can be minimized.

In summary, dairies pose a significant but manageable risk for groundwater pollution, primarily due to nitrate and salt loading. A number of research projects have also shown that pathogens are also a risk for domestic or municipal wells within the immediate vicinity of areas with land application of manure. The dairy industry and other agricultural water users in California, as well as urban and domestic water users, have a high stake in maintaining groundwater quality as it is their main source of water for drinking, washing, and irrigating. To manage and protect groundwater quality in the long run, it is necessary to eliminate the risk for unintended large-scale pollution by:

- Understanding the factors controlling groundwater pollution;
- Reducing the risk through improved agronomic, engineering, and technical methods of nutrient and salt management;
- Spreading the application of organic nitrogen across a larger land area; and
- Evaluating the effectiveness of actions taken to minimize groundwater impacts.

Land values, market demands, and operational costs in the dairy industry are likely to continue and apply pressure for creating dairies with a larger number of cows per facility and per land application area. That in turn will create a push for larger nutrient throughput in the associated cropland to balance the larger number of animals. Increasing the nutrient throughput will increase the risk of groundwater pollution unless the increase is matched with adequate technological and agronomic groundwater protection measures.

We anticipate that in the long term most dairies will need to completely pave animal production areas and to use liquid and solid and manure storage areas that have synthetic liners similar to modern landfills. New air pollution regulations may require that dairies have enclosed manure storage facilities. Those storage facilities are likely to be combined with aerobic digesters and manure treatment systems that remove salts and create a reliable, uniform fertilizer that can easily be managed to meet crop demands. High-precision irrigation and nutrient management practices (similar to developments in other high-nutrient crops such as vegetables) will replace current practices.

Meeting these challenges in an economically and agronomically viable fashion will require the visionary and cooperative initiative of industry, research and teaching institutions, and regulatory agencies. There is much room for innovation beyond current treatment, agronomic, and monitoring practices.

REFERENCES

Harter, T., M. C. Mathews, R. D. Meyer, 2001. Effects of dairy manure nutrient management on shallow groundwater nitrate: a case study. ASAE Meeting Presentation, *ASAE Paper Number 01-2192, 2001 ASAE Annual International Meeting, Sacramento, CA, July 30-August 1, 2001*; 2001.

Harter, T., H. Davis, M. C. Mathews, R. D. Meyer, 2001. Monitoring shallow groundwater nitrogen loading from dairy facilities with irrigated forage crops. ASAE Meeting Presentation, *ASAE Paper Number 01-2103, 2001 ASAE Annual International Meeting, Sacramento, CA, July 30-August 1, 2001*.

Harter, T., H. Davis, M. C. Mathews, R. D. Meyer, 2002. Shallow groundwater quality on dairy farms with irrigated forage crops, *Journal of Contaminant Hydrology* 55 (3-4), pp. 287-315.

Harter, T., R. D. Meyer, M. C. Mathews, 2003. Nonpoint source pollution from animal farming in semi-arid regions: Spatio-temporal variability and groundwater monitoring strategies; in: Ribeiro, L. (Ed.), 2002, *Future Groundwater Resources at Risk, Proceedings of the 3rd International Conference, Lisbon*, Portugal, June 2001; pp. 363-372.

Mathews, M. C., E. Swenson, T. Harter, R. D. Meyer, 2001. Matching dairy lagoon nutrient application to crop nitrogen uptake using a flow meter and control valve. *ASAE Paper Number 01-2105, 2001 ASAE Annual International Meeting, Sacramento, CA, July 30-August 1, 2001*.

Mathews, M. C., 2004. Principles of recycling dairy manures through forage crops, *Proceedings, National Alfalfa Symposium, 13-15 December 2004, San Diego, CA*; UC Cooperative Extension, University of California, Davis 95616

Nakamura, K., T. Harter, Y. Hirono, H. Horino, and T. Mitsuno, 2004. Assessment of root zone nitrogen leaching as affected by irrigation and nutrient management practices. *Vadose zone J., accepted for publication*.

Onsoy, Y. S., T. Harter, T. R. Ginn, W. R. Horwath, 2004. Spatial variability and transport of nitrate in a deep alluvial vadose zone. *Vadose Zone J., accepted for publication*