Nitrate and Salinity in Shallow Groundwater Beneath Dairy Farms in the Central Valley, California

Task Report 1

Project

"Long Term Risk of Groundwater and Drinking Water Degradation from Dairies and Other Nonpoint Sources in the San Joaquin Valley"

Prepared by:

Thomas Harter[1], Megan Young[2], Katherine Lockhart[1]

1. Dept. of Land, Air and Water Resources, University of California, One Shields Avenue, Davis, California, 95616
2. U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025

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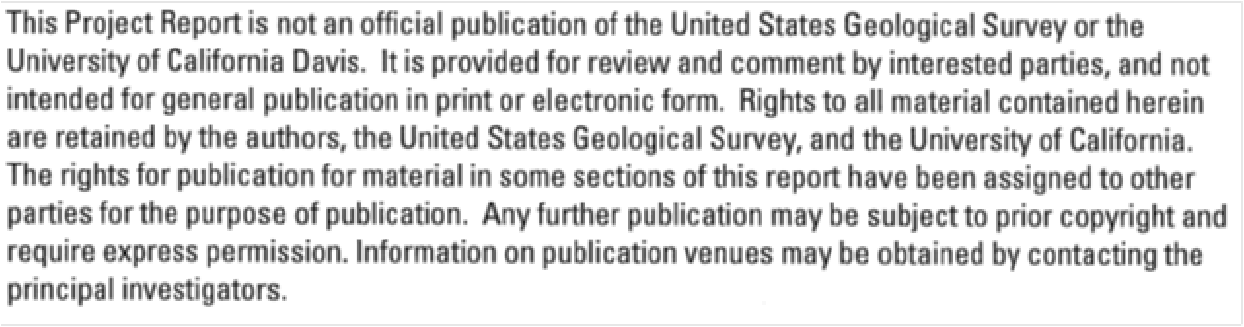

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Abstract

Groundwater samples were collected from two dairies in the northern San Joaquin Valley, where the water table is fairly shallow, and from five dairies in the Tulare Lake Basin, where the water table varies from 15 m (one dairy) to approximately 30 m (four dairies). All but two of the Tulare Lake Basin dairies have been established more than half a century ago. We investigated the effects of various dairy management areas, water table depth, dairy age, and farm nitrogen budget on nitrate, ammonium, and salinity in first encountered groundwater beneath the dairy sites. We find some association between farm nitrogen budget and groundwater nitrate concentration, but more monitoring sites will be needed to ascertain this relationship. Dairy age (older vs. new) is a significant effect only for EC, which may be due to the small sample size. If we also consider correlation between various effects, then dairy age drops out as a significant effect, even for EC. Water table depth is a significant effect for water quality. Total N and EC concentrations at the deep water table dairy sites are much lower for corral and lagoon areas when compared to shallow water table dairy sites. High ammonium-N concentrations are only found adjacent to lagoons at shallow water table dairy sites and in shallow perched groundwater adjacent to lagoons at deep water table dairy sites, but not in groundwater at deep water table dairy sites. Denitrification or lateral displacement and dilution in the deep vadose zone may be significantly impacting nitrate leaching to the deep groundwater table underneath manure lagoons. Groundwater quality below manure-receiving forage crop fields is similar between deep and shallow water table sites and may be affected mostly by farm nitrogen budget and perhaps by dairy age. Salinity is found to be strongly affected by the presence of manure lagoons, and by background concentrations in groundwater.

Further information (publications, related reports, multi-media materials) is available at http://groundwater.ucdavis.edu.

1. Introduction

In California's Central Valley, nitrate contamination of drinking water wells is a significant concern, and there are multiple potential sources of nitrate in this area including septic discharge, synthetic and manure fertilizers, and concentrated animal feeding operations (CAFOs) (Lockhart et al., 2013). Dairies represent the majority of animal feeding operations in California, and have been shown to be potential sources of nitrate and salinity (Bacchus and Barile, 2005; Harter et al., 2002) dissolved organic carbon (DOC) (Chomycia et al., 2008), and pathogens (Demirer and Chen, 2005, McLeod et al 2003) to groundwater. Within individual dairies, there are different land use areas including barns and freestalls, corral areas, liquid waste lagoons, and fields for forage crops (Harter et al., 2002). The latter are often fertilized with animal waste, synthetic fertilizer, or both, each of which may have different impacts on the groundwater.

All dairies investigated by Harter et al., 2002 exhibited very shallow groundwater conditions with water table typically about 3 m below ground surface an with dairies being located on sandy to loamy sand soils. A key question that has arisen from that work is, whether depth to groundwater – most often exceeding 10 m in the San Joaquin Valley and Tulare Lake Basin, and sometimes exceeding even 30 m – plays a significant role in attenuating nitrate leaching from dairies. Other factors that the earlier study did not investigate is the nitrogen budget of dairy as a driving factor of groundwater nitrate (VanderSchans et al., 2009), and also the interaction between depth to groundwater and the leaching from specific dairy management units (lagoon vs corral vs. field with manure applications).

In this project, we investigate the quality of the shallow-most groundwater encountered immediately downgradient of dairy corrals, dairy lagoons, and forage fields and thought to be recharged from these landuse units at two older dairies that were part of the study by Harter et al. (2002) with water table depth of approximately 3 m, one new dairy with water table depth of approximately 15 m, and four dairies (one new, three old) with over 30 m depth to groundwater. For groundwater sampling, we relied on existing groundwater monitoring wells and we also constructed new groundwater monitoring wells. This report presents the results of the ammonium, nitrate, and salinity water quality analyses performed on this monitoring well network.

2. Methods

2.1 Project Area, Wells, and Land Use

Seven dairies were chosen for this study, two of which are located in Stanislaus County in the Lower San Joaquin Valley (referred to as Stan dairies for this study), and five of which are located in Kings and Tulare Counties in the Tulare Lake Basin within the San Joaquin Valley (Kings and Tul dairies) (Table 1). Detailed descriptions of the geology and hydrology at the Stan dairy sites are given in Harter et al., 2002 and Watanabe et al., 2008. The Stan dairies are located in a hydrologically open basin underlain by an unconfined aquifer which receives recharge from precipitation and irrigation. Groundwater levels at the Stan sites are typically between 3 to 7 meters below surface, and therefore highly vulnerable to contamination from land use activities. Soils on the Stan dairies consist of loamy sand to sandy soils, originating from alluvial deposits of the Tuolumne, Stanislaus, and San Joaquin Rivers (Harter et al., 2002, Chomycia et al., 2008). The Kings and Tul dairies are located in the hydrologically closed eastern Tulare Lake Basin, and the top of the water table during the study was between 14 m at one dairy site and 25 to 44 m below surface at the other four dairy sites, with strong seasonal fluctuations in the water table level (up to 10 m) during the course of this study. There are no direct groundwater discharges to surface waters in the area of the Kings and Tul dairies, but there is significant use of groundwater for various purposes including drinking water and irrigation.

2.2 Monitoring Well Design and Monitoring Well Network

Monitoring wells on all the dairies were screened to sample as close to the top of the groundwater table as possible. Harter et al. (2002) demonstrated that the source area for monitoring wells screened just below the water table was typically between 150 m to several hundred meters long and relatively narrow, and therefore the water sampled from these wells is representative of land use immediately upgradient of the well. Monitoring wells are constructed of 5.1 cm diameter PVC pipe. At some of the Kings and Tul well sites, multi-level monitoring wells were constructed of two to three 5.1 cm diameter PVC pipes kept in place by 2.5 cm spacers between the well pipes. Screen depth at Kings and Tul dairy sites vary, but generally vary from 3 m to 6 m in length.

Due to large fluctuations in the groundwater table (driven primarily by pumping for irrigation water) around the Kings and Tul dairies, some nested wells were installed with multiple monitoring wells in a single borehole, each well at a different screen depths in order to consistently obtain shallow groundwater samples with seasonally changing groundwater levels, and to better understand water quality dynamics within the upper portion of the groundwater. Nested wells were installed on three dairies, two in Kings County, and one in Tulare County. Screen lengths varied from 1.5 m to 6 m length at non-overlapping depth, separated by a low-permeable cement-bentonite grout seal between screens. In the Kings and Tul dairies, depths to the top of the well screens ranged from 11.6 to 51.8 meters.

All dairies in this study had similar land management units, although the dairies varied in size and length of time that the land had been used for dairy operations. The land management units on the dairies consisted of corrals and freestalls where the animals were housed, liquid manure storage ponds (waste lagoons), and forage crop fields which were irrigated and fertilized with dry manure and diluted liquid manure from the waste lagoons. Some of the dairies may also have supplemented manure applications to the fields with synthetic fertilizer applications.

Table 1. Summary of key dairy characteristics and monitoring well network design used in this study. The three numbers indicate the total number of monitoring well sites (counting multiple nested wells as one site), the total number of monitoring wells sampled at least once (counting multiple, nested wells separately), and the number of monitoring wells sampled at least three times during the project sampling period September 2007 through October 2009.

Dairy & Location	Total Monitoring Well Sites / Wells	Lagoon wells	Corral Wells	Field Wells	Mixed Land Use Wells	Up-gradient wells	Age of Dairy	Depth to Ground-water	Soil Type
Stanislaus County									
Dairy 37-42	14 / 14 / 9	1/1/1	2/2/2	10/10/5	--	1/1/1	old	shallow	sandy loam
Dairy 37-39	9 / 9 / 8	1/1/1	4/4/4	2/2/1	1/1/1	1/1/1	old	shallow	sandy loam
Kings County									
Dairy 36-15	7 / 17 / 15	3/7/6	1/2/2	3/8/7	--	--	old	deep	sandy loam
Dairy 36-19	7 / 21 / 17	1/2/1	3/10/9	2/6/5	1/3/2	--	old	deep	sandy loam
Tulare County									
Dairy 36-04	5 / 10 / 8	1/2/2	1/1/0	1/4/4	--	2/3/2	new	deep	sandy loam
Dairy 36-11	4 / 4 / 4	1/1/1	1/1/1	1/1/1		1/1/1	old	deep	sandy loam
Dairy 36-24	2 / 2 / 2	1/1/1	--	--	--	1/1/1	new	deep	sandy loam
Dairy 36-27	3 / 3 / 3	1/1/1	1/1/1	1/1/1	--	--	new	inter-mediate	sandy loam
Total	**51/80/66**	**10/16/14**	**13/21/19**	**20/32/24**	**2/4/3**	**6/7/6**			

2.3 Sample Collection

Groundwater samples were collected from monitoring wells installed on two Stanislaus County dairies (Stan dairies), two Kings County dairies, and three Tulare Country dairies (Kings and Tul dairies) for analysis of water level depth, nitrate, ammonium, and electrical conductivity, on 17 sampling dates, spaced approximately 6 weeks apart, beginning September 2007 and ending October 2010. Prior to sample collection, wells were purged with a stainless steel, variable speed submersible sampling pump

(Grundfos) attached to Teflon tubing. While purging, the water was monitored for temperature, electrical conductivity, pH, ORP, and dissolved oxygen. Samples were collected after a minimum of five well volumes were removed and field water quality parameters had stabilized. Once purging was complete, field water quality parameters (temperature, Eh, pH, EC, DO) were measured and recorded. Samples for nitrate and ammonium analysis were filtered at the time of sample collection by passing the water through a 0.45 micron filter connected to the pump outlet. Samples were collected into 50 mL wide-mouth Nalgene HDPE sample bottles, frozen and stored at -20°C upon return to the UC Davis Analytical Laboratory (DANR) for chemical analysis within 30 days.

2.4 Analytical Methods

2.4.1. Field Measurements of Water Quality

Field measurements for temperature, Eh, pH, EC, and DO were performed using a YSI 556 MPS water quality meter installed into a flow through cell. Each day, the water quality meter was calibrated using calibration solutions, following the instructions for the YSI water quality meter (http://www.ysi.com/productsdetail.php?556MPS-21).

2.4.2. Chemical Analysis: Nitrate and Ammonium

Samples were analyzed for a large suite of nutrient and chemical concentrations at the UC Davis Analytical Laboratory (DANR). Samples were analyzed for ammonium-N, nitrate-N, and nitrite-N using the Cadmium Reduction Flow Injection Method, Standard Method 4500-NO3-N I (Clesceri et al., 1998). This method reduces any nitrate present in the sample to nitrite, thus the result is total nitrate plus nitrite. However, for groundwater samples in our study area, it is typical for nitrite to be negligible. For quality control, field blanks and field duplicates were collected on every 10th well sample. Nitrate was not detected in any field blanks and average percent difference between sample and field duplicate was 0.5 mg N/L.

2.4.4. Statistical Analysis

Descriptive statistical analyses were performed using the software package Statistica (Statsoft, 2013). Analysis of Variance was performed to determine statistical significance of differences between grouped means.

3. Results

3.1 Nitrate and Salinity: General Statistical Findings

Within this chapter “project monitoring wells” refers to all monitoring wells for which samples were collected during this project. This includes “upgradient monitoring wells” whose source area is upgradient and outside of the dairy. “Dairy monitoring wells” are those project monitoring wells for which we hypothesize that their source area is within the dairy. We have divided each dairy into three management units: corrals, liquid manure lagoons, and fields receiving manure (solid or liquid or both). Project monitoring wells are divided depending on their hypothesized source areas into “corral wells”, “lagoon wells”, and “field wells”. Results for the upgradient wells will be identified specifically as “upgradient wells” in this report, they may be located within or outside the dairy, but their source area is not thought to be affected by the three management units listed above.

Table 2: Date, season, irrigation season, and number of samples collected from project monitoring wells. The date refers to the first day of the specific sampling campaign. In parantheses, the number of samples on a given sampling trip date with non-detectable levels of the analyte.

Trip Date	***Season***	***Irrigation Season***	***# Nitrate (# non-detect***		***# Ammonium (# non-detect)***		***# EC***	***reason for missing EC data***
9/17/2007	fall	on	68	(1)	68	(57)	58	bailed samples/water volume too small
11/5/2007	fall	off	70	(1)	70	(45)	64	bailed samples/water volume too small
1/3/2008	winter	off	45	(1)	45	(42)	45	
2/18/2008	winter	off	63	(1)	63	(52)	62	water volume too small
4/2/2008	spring	off	56	(1)	56	(51)	56	
5/12/2008	spring	on	61	(1)	61	(53)	61	
6/23/2008	summer	on	62	(1)	62	(55)	59	1 well bailed; 2 field records missing
8/4/2008	summer	on	58	(0)	58	(55)	58	
9/9/2008	fall	on	54	(0)	55	(52)	54	
10/27/2008	fall	off	54	(1)	54	(49)	54	
12/15/2008	winter	off	53	(0)	53	(48)	52	1 well bailed;
2/3/2009	winter	off	60	(1)	60	(55)	60	
3/19/2008	spring	off	58	(1)	58	(52)	58	
5/28/2009	spring	on	57	(0)	57	(48)	57	
7/9/2009	summer	on	54	(1)	54	(45)	54	
8/17/2009	summer	on	53	(0)	53	(48)	53	
10/1/2009	fall	off	49	(0)	49	(42)	49	
TOTAL			**975**	**(11)**	**975**	**(849)**	**954**	

The dataset consists of nitrate-N, ammonium-N, and electrical conductivity data measured in the field except in few instances, where the volume of water recovered was too small to be measured in the field. In some (but not all) of those cases, EC was measured in the laboratory. For the analysis here, we do not distinguish between the two measurement types for EC.

Samples were collected on 17 sampling dates between September 2007 and October 2009. A total of 975 water samples were collected from monitoring wells, for which nitrate-N and ammonium-N was determined. Electrical conductivity measurements are available for 954 of those 975 water samples (Table 2).

Of the 975 water samples, ammonium-N was detected above the measurable detection level (MDL) in only 126 samples. In contrast, nitrate-N was detected above the MDL in all but 11 samples (964 samples). There are no cases, where both nitrate-N and ammonium-N were below the detection limit of 0.05 mg/L. 115 samples (10%) have detection of both nitrate-N and ammonium-N.

To evaluate the impact on groundwater quality, it is helpful to also consider the sum of ammonium-N and nitrate-N (where nitrate-N is analytically the sum of nitrate-N and nitrite-N, see methods). This “total N”, however, does not include any dissolved organic nitrogen present in groundwater (Chomycia et al, 2008).

Table 3: Basic statistical measures of nitrate-N [mg/L], ammonium-N [mg/L], total N [mg/L] (the sum of nitrate-N and ammonium-N), and electrical conductivity [uS/cm] in XX monitoring wells, sampled as often as 17 times between September 2007 and October 2009.

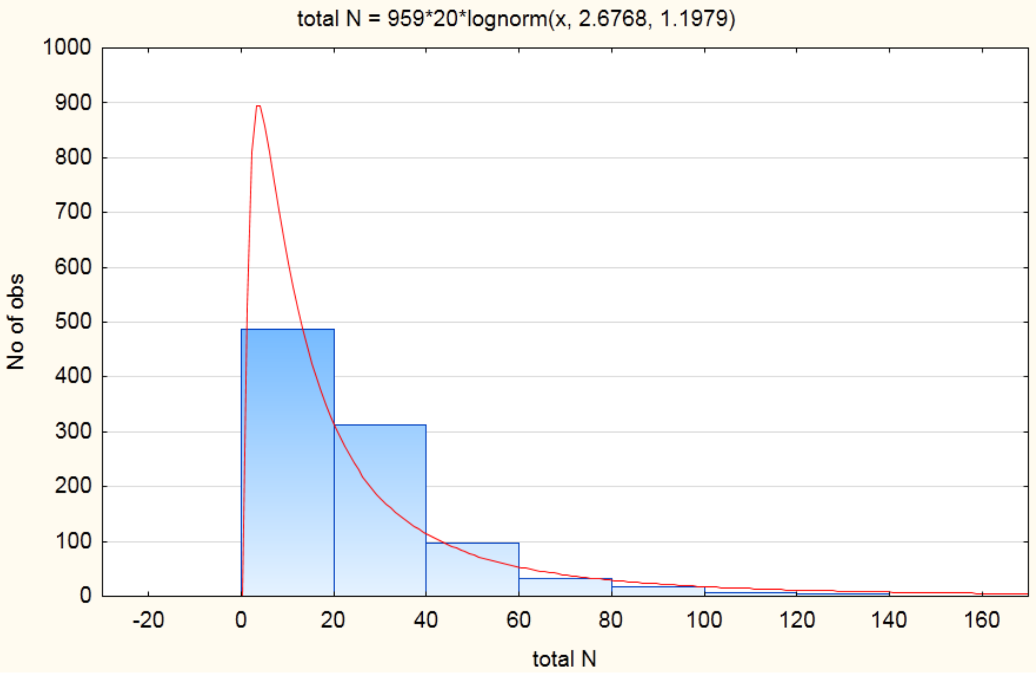
	N	*Mean*	*Geom. mean*	*Median*	*Min*	*Max*	*25th Q*	*75th Q*	*95thQ*	*StD*	*Skewness*
total N	975	29.7	15.3	20.0	0.4	588	9.00	33.9	78.7	50.4	6.7
nitrate-N	975	26.7	13.0	19.3	0.025	557	8.1	32.1	68.8	45.1	7.4
ammonium-N	975	3.1	0.04	0.025	0.025	260	0.025	0.025	1.47	18.1	7.8
EC	954	1556	1319	1510	251	9822	943	1945	2668	1028	3.8

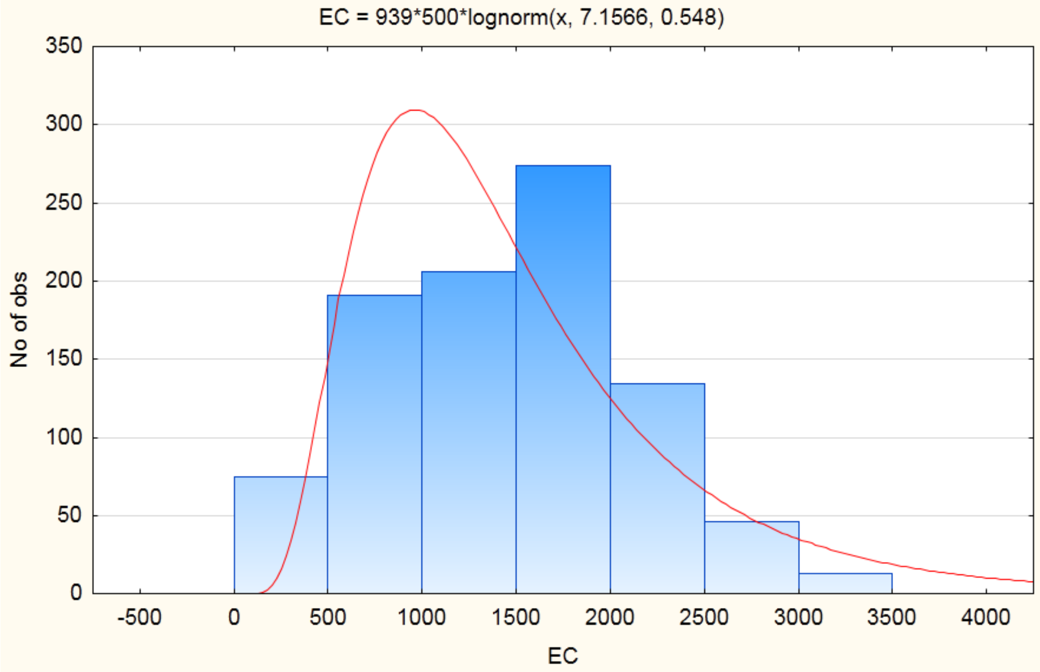
Nitrate-N and ammonium-N concentrations across the sample population have a strong right-skewed distribution (tail to the right, Figure 2), as has been found previously (Harter et al., 2002). Total N is similarly right-skewed distributed. The electrical conductivity also has a right-skewed distribution (Figure 1). Nitrate-N exceeds the maximum contaminant level for nitrate-N, 10 mg/L, in 670 samples (69%), total N exceeds 10 mg/L in 700 samples of the 975 samples (72%).

The statistical distribution of nitrate-N, total N, and EC measured over time at individual monitoring wells (up to 17 samples per monitoring well) does not generally exhibit such right-skewed distribution. On the 66 monitoring wells with at least 3 nitrate-N samples, the average of the skewness coefficient (of multiple samples taken at different times in the same well) is 0.09. At one quarter of monitoring wells, the nitrate-N skewness coefficient is -0.5 or less, at one quarter of the monitoring wells, the nitrate-N skewness coefficient over the sampling period is 0.7 or larger. For EC the average of the skewness coefficient at each of 64 wells with 3 measurements or more is -0.21. One quarter of the monitoring wells have a skewness coefficient in the EC samples of -0.9 or less, one quarter of the monitoring wells have a skewness coefficient of 0.2 or more. As a result, at individual monitoring wells, the mean, median, and geometric mean of EC and nitrate-N are often very similar.

Ammonium-N is below the detection limit throughout the sampling period at most wells. For total N, the average skewness coefficient is therefore similar to that for nitrate-N: 0.04.

Figure 1: Histogram of total N [mg/L], defined here as the sum of ammonium-N and nitrate-N (top) and of electrical conductivity (EC). Samples with non-detect levels are here considered to have values at half of the method detection limit (MDL) of 0.05 mg/L. Not included are unsampled events, and 17 samples, where total N exceeds 150 mg/L. The lognormal distribution has a geometric mean for total N of 14.5 mg/L and for electrical conductivity of 1,283 uS/cm (lower than in Table 2 due to removing the 17 highest nitrate samples).





The 975 individual samples are not statistically independent of each other. For further analysis, it is useful to consider not the distribution across the entire analytical dataset, but the distribution between well sites across horizontal space (mapping), the vertical distribution (in multi-level wells, vertical trend analysis), and possibly the temporal distribution (temporal trend analysis). This allows us to account for spatial and temporal correlations that would otherwise bias a statistical analysis. Furthermore, we are interested to divide the dataset spatially (horizontally) by management unit (corral, lagoon, field, upgradient), by dairy age, by water table depth (shallow or deep), or by any combination of these group attributes to determine the role of these factors with respect to total N and EC.

3.2 Nitrogen and Salinity Impact to Groundwater: Spatial Variations between Management Units, Deep and Shallow Water Table Sites, Older and New Dairies.

Based on regional groundwater flow direction and nearby land uses, we assigned specific dairy management units to each well location (Table 1). Table 4 provides a summary of basic statistical measures across all water quality samples, grouped by management units.

Table 4: Basic statistical measures of total N, nitrate-N, ammonium-N, and salinity (EC) in water samples, grouped by management unit assigned to each water sample (via the associated well). This includes samples from monitoring wells, where only 1 or 2 samples have been collected.

	Mgmt Unit	*Valid N*	*Mean*	*Geometric Mean*	*Median*	*Lower Quartile*	*Upper Quartile*	*95th Percentile*	*Std. Dev.*	*Skew-ness*
total N	corral	280	19.4	12.4	16.3	8.3	25.8	53.4	19.5	5.7
nitrate-N	corral	280	18.2	11.3	15.8	7.8	25.3	51.0	15.1	1.6
ammonium-N	corral	280	1.2	0.0	0.0	0.0	0.0	1.1	9.2	12.8
EC	corral	274	1397	1239	1369	1006	1728	2883	660	0.8
total N	field	376	29.7	24.9	26.3	17.9	38.2	70.4	17.6	1.4
nitrate-N	field	376	29.7	24.7	26.3	17.8	38.2	70.4	17.6	1.4
ammonium-N	field	376	0.1	0.0	0.0	0.0	0.0	0.1	0.7	12.4
EC	field	368	1648	1577	1717	1418	1950	2343	455	-0.2
total N	lagoon	188	47.2	8.1	5.9	1.6	27.0	275.7	105.5	3.3
nitrate-N	lagoon	188	33.3	4.0	3.5	1.1	20.4	259.6	94.9	3.9
ammonium-N	lagoon	188	13.9	0.1	0.0	0.0	0.0	111.1	37.9	3.3
EC	lagoon	183	2010	1429	1521	694	2451	7363	1920	2.4
total N	multiple	50	29.1	11.1	8.7	2.5	72.9	89.2	35.0	0.9
nitrate-N	multiple	50	29.1	11.1	8.7	2.5	72.9	89.0	34.9	0.9
ammonium-N	multiple	50	0.0	0.0	0.0	0.0	0.0	0.1	0.1	6.6
EC	multiple	49	990	707	584	303	1970	2351	792	0.7
total N	upgrdnt	81	25.1	18.4	21.3	8.9	42.8	47.9	17.0	0.2
nitrate-N	upgrdnt	81	25.1	18.4	21.3	8.9	42.8	47.9	17.0	0.2
ammonium-N	upgrdnt	81	0.0	0.0	0.0	0.0	0.0	0.1	0.1	7.6
EC	upgrdnt	80	985	876	726	625	1071	1995	521	1.1

Table 4, however, represents the unbalanced full dataset, with wells that are sampled at only a few sampling dates and others that are sampled at 17 sampling dates. Also, some well sites have multiple, nested monitoring wells, while others have only a single monitoring well. Finally, data collected in the same well and at the same well site are significantly correlated in time and not independent of each other.

At well sites with nested monitoring wells, we next consider only the water quality samples at the monitoring well closest to the water table (first encountered groundwater) on any given sampling date. Over time, the samples collected at these nested well sites may come from different monitoring wells, as groundwater levels generally trended lower with time over the sampling period . Thus, for this analysis we have, at each well site, on a given date, at most one water sample data point. From this well site specific time series of water quality data, we generate a single representative value at each well site. Here we specifically use the median value of all samples collected between September 2007 and October 2009 because it is more robust against outliers than the mean, although it will be close to the mean in most cases due to the relatively symmetric distribution of sample values in individual well site time series (see above). The median (over time) at each well site allows each well site to be represented with equal weight, regardless of the number of samples taken throughout the sampling period, and regardless of the number of multi-level well screens (if any) at the site.

Tables 5-8 provide a summary of the statistics on the representative well site values for EC, nitrate-N, ammonium-N, and total N. Statistics are grouped by dairy management units, by the two water table depth categories, and by the two dairy age categories.

Table 5: Well-site median of electrical conductivity: grouped means, standard deviations, and standard error. Groups that are not management unit specific include two sites classified as "multiple" management units.

Mgmt Unit	*Age/WT*	*Valid N*	*Mean*	*Std. Dev.*	*Std. Error*
(all)	(all)	44	1,655	1,164	176
(all)	new	8	890	429	152
(all)	old	36	1,825	1,210	202
(all)	deep	26	1,285	608	119
(all)	shallow	18	2,188	1,541	363
corral	(all)	12	1,619	716	207
corral	new	1	1,060		
corral	old	11	1,670	728	219
corral	deep	6	1,136	379	155
corral	shallow	6	2,103	650	265
field	(all)	15	1,643	419	108
field	new	2	1,333	626	443
field	old	13	1,691	392	109
field	deep	8	1,683	366	129
field	shallow	7	1,598	499	188
lagoon	(all)	10	2,145	2,171	687
lagoon	new	3	782	277	160
lagoon	old	7	2,729	2,392	904
lagoon	deep	8	1,348	772	273
lagoon	shallow	2	5,334	3,583	2,534
upgrdnt	(all)	5	926	594	266
upgrdnt	new	2	522	142	101
upgrdnt	old	3	1,196	651	376
upgrdnt	deep	3	588	152	88
upgrdnt	shallow	2	1,434	712	504

Table 6: Well-site median of ammonium-N: grouped means, standard deviations, and standard error. Groups that are not management unit specific include two sites classified as "multiple" management units.

Mgmt Unit	*Age/WT*	*Valid N*	*Mean*	*Std. Dev.*	*Std. Error*
(all)	(all)	51	3.2	16.0	2.2
(all)	new	10	0.0	0.0	0.0
(all)	old	41	4.0	17.8	2.8
(all)	deep	28	0.0	0.0	0.0
(all)	shallow	23	7.0	23.6	4.9
corral	(all)	13	0.7	2.4	0.7
corral	new	2	0.0	-	-
corral	old	11	0.8	2.6	0.8
corral	deep	7	0.0	-	-
corral	shallow	6	1.5	3.5	1.4
field	(all)	20	0.5	2.0	0.4
field	new	2	0.0	-	-
field	old	18	0.6	2.1	0.5
field	deep	8	0.0	-	-
field	shallow	12	0.8	2.6	0.7
lagoon	(all)	10	14.3	35.2	11.1
lagoon	new	3	0.0	-	-
lagoon	old	7	20.5	41.4	15.7
lagoon	deep	8	0.0	0.0	0.0
lagoon	shallow	2	71.6	54.6	38.6
upgrdnt	(all)	6	0.0	0.0	0.0
upgrdnt	new	3	0.0	0.0	0.0
upgrdnt	old	3	0.0	-	-
upgrdnt	deep	4	0.0	0.0	0.0
upgrdnt	shallow	2	0.0	-	-

Table 7: Well-site median of nitrate-N: grouped means, standard deviations, and standard error. Groups that are not management unit specific include two sites classified as "multiple" management units.

Mgmt Unit	*Age/WT*	*Valid N*	*Mean*	*Std. Dev.*	*Std. Error*
(all)	(all)	51	31.1	48.4	6.8
(all)	new	10	15.1	13.9	4.4
(all)	old	41	35.0	53.0	8.3
(all)	deep	28	18.2	15.9	3.0
(all)	shallow	23	46.8	67.5	14.1
corral	(all)	13	21.6	15.2	4.2
corral	new	2	20.7	3.8	2.7
corral	old	11	21.7	16.6	5.0
corral	deep	7	14.1	7.8	3.0
corral	shallow	6	30.3	17.5	7.2
field	(all)	20	32.5	21.1	4.7
field	new	2	38.2	2.7	1.9
field	old	18	31.9	22.2	5.2
field	deep	8	33.3	19.6	6.9
field	shallow	12	32.0	23.0	6.6
lagoon	(all)	10	42.9	104.3	33.0
lagoon	new	3	4.3	3.2	1.8
lagoon	old	7	59.4	123.5	46.7
lagoon	deep	8	11.4	11.8	4.2
lagoon	shallow	2	169.0	239.0	169.0
upgrdnt	(all)	6	21.6	18.0	7.4
upgrdnt	new	3	6.9	2.4	1.4
upgrdnt	old	3	36.3	12.5	7.2
upgrdnt	deep	4	10.8	7.9	4.0
upgrdnt	shallow	2	43.4	4.2	3.0

Table 8: Well-site median of total N (sum of nitrate-N plus ammonium-N): grouped means, standard deviations, and standard error. Groups that are not management unit specific include two sites classified as "multiple" management units.

Mgmt Unit	*Age/WT*	*Valid N*	*Mean*	*Std. Dev.*	*Std. Error*
(all)	(all)	51	34.4	54.0	7.6
(all)	new	10	15.1	13.9	4.4
(all)	old	41	39.1	59.0	9.2
(all)	deep	28	18.2	15.9	3.0
(all)	shallow	23	54.0	74.7	15.6
corral	(all)	13	22.2	14.6	4.1
corral	new	2	20.7	3.8	2.7
corral	old	11	22.5	16.0	4.8
corral	deep	7	14.1	7.8	2.9
corral	shallow	6	31.7	15.6	6.4
field	(all)	20	33.0	20.6	4.6
field	new	2	38.2	2.7	1.9
field	old	18	32.4	21.7	5.1
field	deep	8	33.3	19.6	6.9
field	shallow	12	32.8	22.2	6.4
lagoon	(all)	10	57.9	116.3	36.8
lagoon	new	3	4.3	3.2	1.8
lagoon	old	7	80.8	135.0	51.0
lagoon	deep	8	11.6	12.1	4.3
lagoon	shallow	2	242.9	187.5	132.6
upgrdnt	(all)	6	21.7	18.1	7.4
upgrdnt	new	3	6.9	2.4	1.4
upgrdnt	old	3	36.5	12.6	7.3
upgrdnt	deep	4	10.8	7.9	4.0
upgrdnt	shallow	2	43.6	4.2	3.0

With the time series aggregated into medians and with only the uppermost water quality sample being considered at nested well sites, the mean nitrate-N is 31.1 mg/L, the mean ammonium-N is 3.2 mg/L, and the mean total N is 34.4 mg/L. The nitrate-N is slightly higher than on the original disaggregated dataset.

There is a significant difference between dairies that have been operating for more than 10-20 years (Dairy Age: “old”) and those that have been constructed within less than 10 years before the sampling campaign (Dairy Age: “new”). The new dairies all exhibit water table depth exceeding 14 – 30 m. Among the 10 well sites at three new dairies, the mean (of the site median) nitrate-N was 15.1 mg/L, while it was 35.0 mg/L at the 41 older dairy well sites. Overall, total N is dominated by nitrate-N, hence, mean total N levels at new and older dairy sites are 15.1 mg/L and 39.1 mg/L, respectively. Similarly, the contrast in mean (of site median) EC is statistically significant with levels of 890 uS/cm at new dairy sites and 1,825 uS/cm at older dairy sites.

A strong contrast in grouped mean nitrate and EC values is also present between well sites located over shallow groundwater (less than 6 m depth to water table) and well sites located over deeper or deep groundwater (14 m to 40 m depth to water table). The mean (of median site) nitrate-N at 28 sites with deep water table is 18.2 mg/L. The same mean is 46.8 mg/L at the 23 sites with shallow water table (18.2 mg/L and 54.0 mg/L for total N, respectively). This contrast is mirrored by the EC mean of well site medians: 1,285 uS/cm at deep water table well sites and 2,188 at shallow water table well sites.

We can also consider the management unit as a factor and investigate contrasts in means between management units. The mean (of site median) nitrate-N is lowest at sites designated as “corral” and as “upgradient” (21.6 mg/L). For “field” sites, the mean nitrate-N is 32.5 mg/L and for “lagoon” sites, the mean nitrate-N is 42.9 mg/L. Means of total N differ by less than 5% from that for nitrate-N except for “lagoon” sites, where ammonium-N averages 14.3 mg/L. At other sites, ammonium-N is most commonly below the detection limit.

For salinity (measured as EC), the “upgradient” sites are also lowest, with a mean of 926 uS/cm, “corral” sites have a mean (1619 uS/cm) very similar to “field” sites (1643 mS/cm), and the highest mean, as for nitrate-N, is found at “lagoon” sites, at 2145 mS/cm.

Within specific management units, Tables 5-8 also show the grouped means for older vs. new dairies and for shallow vs. deep water table sites. Large contrasts are observed for nitrate-N and ammonium-N for the following cases:

- Nitrate-N at “corral” sites averages to be twice as high at shallow sites than at deep sites
- Nitrate-N at “lagoon” sites is much higher in older dairies than in new dairies, and where the water table is shallow (both are older dairies) than where the water table is deep (even at very old dairies)

- “upgradient” mean nitrate-N is much higher at older dairies, and at dairies with shallow water table
- Ammonium-N is elevated only at older dairies with shallow water table.

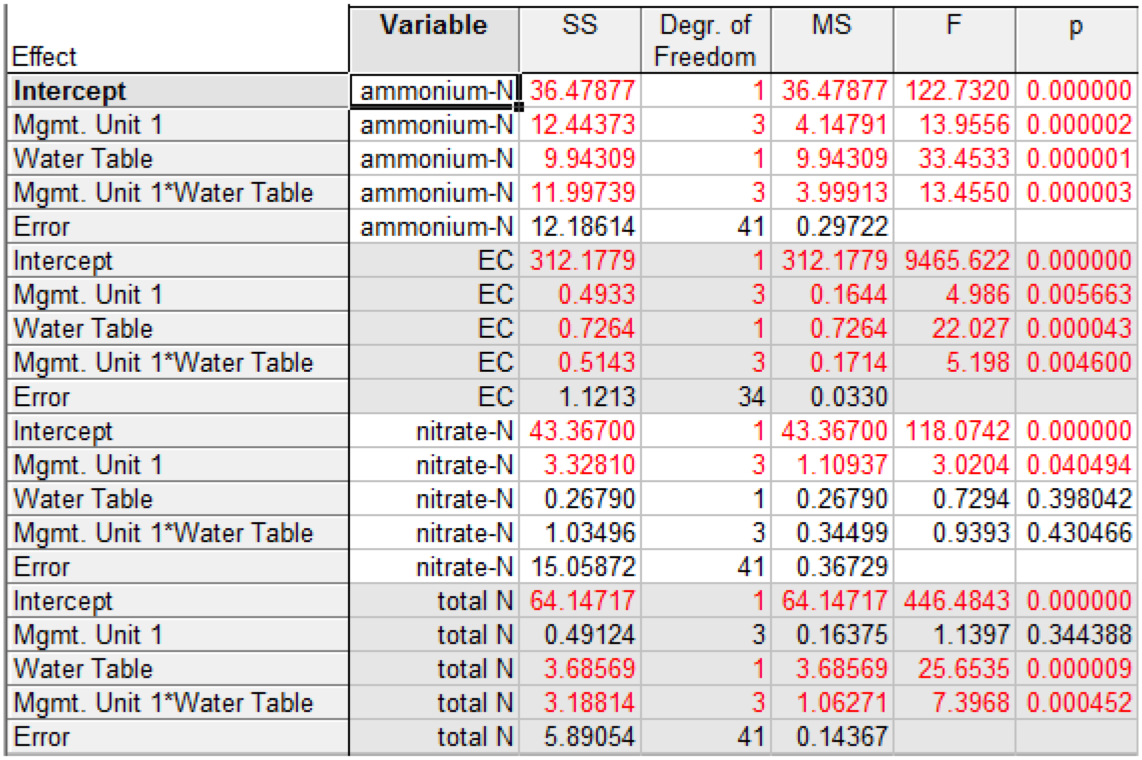
Contrasts in means of EC are most prominent in the following cases:

- Older dairies have higher EC than newer dairies throughout all management units, but the contrast is particularly strong at “lagoon” sites and at “upgradient” locations, even though “upgradient” locations are not thought to be affected by the presence of the dairy operation. Other factors correlated to dairy age may be the control on this outcome.
- At “field” sites, depth to water table does not affect the mean EC. But contrasts due to water table depth are particularly strong at “upgradient” and “lagoon” sites. Shallow water table wells have much higher overall salinity than deep water table wells.

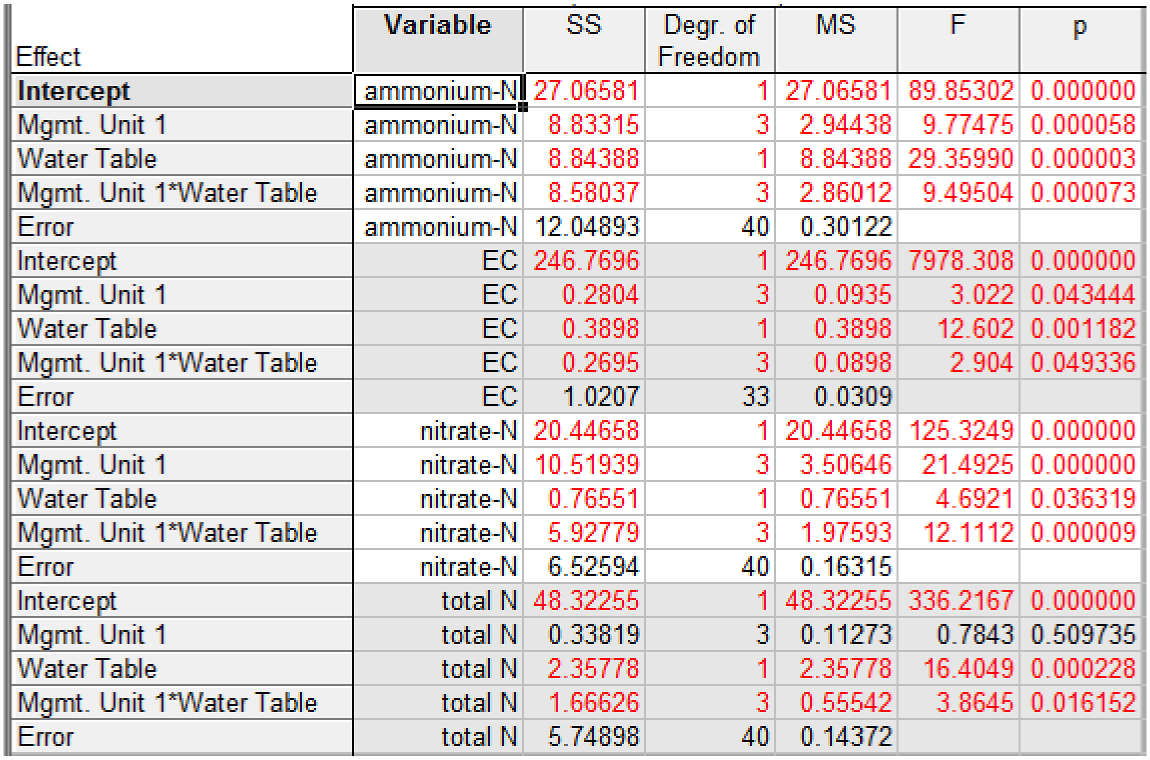
Not all of these contrasts are statistically significant, owing to the large variability in water quality between well sites and the limited number of well sites within each group. To test for statistical significance, we take the log10 transform of the site median water quality value (for ammonium-N, nitrate-N, total N, EC), which is closer to normal distributed (less skewed) than the sample of median values. We perform an analysis of variance (ANOVA) on the log10 of the median values. Management unit by itself is not a significant effect for any of the four analytes. Dairy age (older vs. new) is a significant effect only for EC. Water table depth is a significant effect for ammonium-N, total N, and EC, but not for nitrate-N. If we also consider the interaction between effects, then dairy age drops out as a significant effect, even for EC.

We therefore considered only management unit, water table depth (deep / shallow) and the interaction between management unit and water table depths in the final ANOVA. For ammonium-N and EC, the management unit, water table depth, and their interactions are all three statistically significant factors. For nitrate-N, only the management unit is a statistically significant factor, but for total N, water table depth and the interaction between water table depth and management unit are statistically significant factors. If we exclude one outlier well site, categorized as “shallow” and “lagoon”, with occasionally excessive levels of nitrate-N and ammonium-N (Figure 2), then, for nitrate-N, the factors management unit, water table depth, and their interaction are all statistically significant,.

Figure 2: Complete factorial Analysis of Variance (ANOVA) of the well site median water quality at first encountered groundwater over the sampling period. Final factors considered are management unit (upgadient, corral, lagoon, field) and water table depth (deep, shallow). We excluded two well sites classified as "multiple" from this analysis. The analysis was performed for all for water quality parameters: ammonium-N, nitrate-N, total N, and EC. "SS" and "MS" are the sum of square error and the mean error, respectively. "F" is the F statistic, and "p" is the p-value. Factors or interactions that have a p value less than 0.05 are considered statistically significant. The first table shows the results for the full dataset, the second excludes one lagoon well site that had excessively high ammonium and nitrate levels at some sampling dates (site considered an outlier).

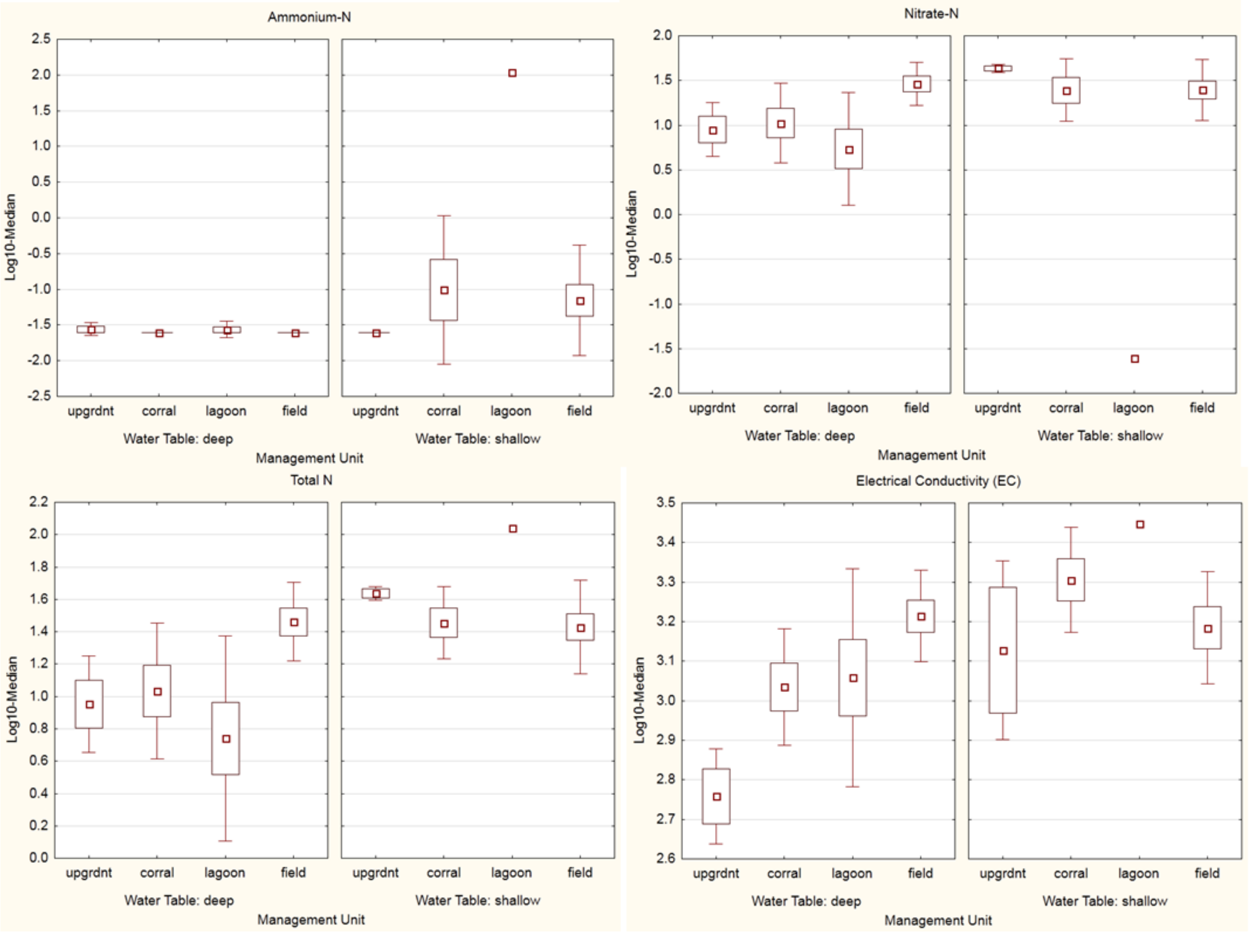


Effect	**Variable**	SS	Degr. of Freedom	MS	F	p
Intercept	ammonium-N	36.47877	1	36.47877	122.7320	0.000000
Mgmt. Unit 1	ammonium-N	12.44373	3	4.14791	13.9556	0.000002
Water Table	ammonium-N	9.94309	1	9.94309	33.4533	0.000001
Mgmt. Unit 1*Water Table	ammonium-N	11.99739	3	3.99913	13.4550	0.000003
Error	ammonium-N	12.18614	41	0.29722		
Intercept	EC	312.1779	1	312.1779	9465.622	0.000000
Mgmt. Unit 1	EC	0.4933	3	0.1644	4.986	0.005663
Water Table	EC	0.7264	1	0.7264	22.027	0.000043
Mgmt. Unit 1*Water Table	EC	0.5143	3	0.1714	5.198	0.004600
Error	EC	1.1213	34	0.0330		
Intercept	nitrate-N	43.36700	1	43.36700	118.0742	0.000000
Mgmt. Unit 1	nitrate-N	3.32810	3	1.10937	3.0204	0.040494
Water Table	nitrate-N	0.26790	1	0.26790	0.7294	0.398042
Mgmt. Unit 1*Water Table	nitrate-N	1.03496	3	0.34499	0.9393	0.430466
Error	nitrate-N	15.05872	41	0.36729		
Intercept	total N	64.14717	1	64.14717	446.4843	0.000000
Mgmt. Unit 1	total N	0.49124	3	0.16375	1.1397	0.344388
Water Table	total N	3.68569	1	3.68569	25.6535	0.000009
Mgmt. Unit 1*Water Table	total N	3.18814	3	1.06271	7.3968	0.000452
Error	total N	5.89054	41	0.14367		



Effect	Variable	SS	Degr. of Freedom	MS	F	p
Intercept	ammonium-N	27.06581	1	27.06581	89.85302	0.000000
Mgmt. Unit 1	ammonium-N	8.83315	3	2.94438	9.77475	0.000058
Water Table	ammonium-N	8.84388	1	8.84388	29.35990	0.000003
Mgmt. Unit 1*Water Table	ammonium-N	8.58037	3	2.86012	9.49504	0.000073
Error	ammonium-N	12.04893	40	0.30122		
Intercept	EC	246.7696	1	246.7696	7978.308	0.000000
Mgmt. Unit 1	EC	0.2804	3	0.0935	3.022	0.043444
Water Table	EC	0.3898	1	0.3898	12.602	0.001182
Mgmt. Unit 1*Water Table	EC	0.2695	3	0.0898	2.904	0.049336
Error	EC	1.0207	33	0.0309		
Intercept	nitrate-N	20.44658	1	20.44658	125.3249	0.000000
Mgmt. Unit 1	nitrate-N	10.51939	3	3.50646	21.4925	0.000000
Water Table	nitrate-N	0.76551	1	0.76551	4.6921	0.036319
Mgmt. Unit 1*Water Table	nitrate-N	5.92779	3	1.97593	12.1112	0.000009
Error	nitrate-N	6.52594	40	0.16315		
Intercept	total N	48.32255	1	48.32255	336.2167	0.000000
Mgmt. Unit 1	total N	0.33819	3	0.11273	0.7843	0.509735
Water Table	total N	2.35778	1	2.35778	16.4049	0.000228
Mgmt. Unit 1*Water Table	total N	1.66626	3	0.55542	3.8645	0.016152
Error	total N	5.74898	40	0.14372		

Figure 3: Log10-median site water quality. Box plots of mean (central square), standard error of the mean (box), and standard deviation (bars), grouped by management unit and well depth. Results are shown for Ammonium-N (top left) and nitrate-N (top right), and for total N (bottom left) and EC (bottom right). The four management units are compared for deep water table sites (left panel) and for shallow water table sites (right panel). Within each panel, the four management units shown are "upgradient", "corral", "lagoon", and "field" (from left to right). These results do not include data from one outlier well site categorized as "lagoon" and "shallow". Note that log10 values of "0", "1", "2", and "3" on the y-axis denote "1", "10", "100", and "1000", respectively, after transformation to regular values. The log10 values of "0.5", "1.5", and "2.5" on the y-axis denote "3.2", "32", and "316", respectively, after transformation to regular values. The half-MDL used to denote nitrate-N and ammonium-N measurements below the detection limit is 0.025 mg/L, which corresponds to -1.6 on the log10 scale.



3.3 Changes of Nitrogen and Salinity with Depth in Multi-level Monitoring Wells

For all sampling dates, at all multi-level monitoring well sites, we computed the difference between subsequent well screens, if they were sampled. Differences are computed such that a positive difference indicates that the higher concentration was encountered at the shallower of the two well screens compared. As an initial step, we consider the values of differences but neglect the actual vertical distance between screens as a factor.

There are 29 monitoring wells with an overlying monitoring well. All of the multi-level sites are located where water levels exceeds 24 m below ground surface. There are only few observations of ammonium-N exceeding 0.2 mg/L in these wells, and these are always associated with the shallow-most of multiple, nested observation screens. For nitrate-N, the median difference (at up to 17 sample dates) at any given well screen to its next lower well screen varies from -20 mg/L (increasing nitrate with depth) to 15 mg/L (decreasing nitrate with depth). The lower quartile of these medians, is -1.2 mg/L and the upper quartile is 1.9 mg/L, centered around 0.1 mg/L. Hence, among all screen pairs, differences between overlying intervals tend to be within a few mg/L and the gradient may be decreasing or increasing nitrate-N with depth.

Similarly, for salinity, the median difference (at up to 17 sample dates) at any given well screen to its next lower well screen varies widely from -470 uS/cm to over 2000 uS/cm with the lower and upper quartile of these medians at-30 and 270 uS/cm, but centered (median) at 20 uS/cm, not significantly different from zero.

4. Discussion and Conclusions

The data collected largely confirm earlier findings (Harter et al., 2002), in particular with respect to nitrate and salinity impacts from dairies that have been operated for more than 20 years in areas with shallow water table. More than two-thirds of all samples exceed the drinking water quality standard for nitrate and the average site median in each of the four management units (including "upgradient") exceeds the drinking water standard.

Unlike earlier studies, this project included sites with water table exceeding 40 to 100 feet. The two dairies with shallow water table (approximately 10 feet) are both located in Stanislaus County west of Highway 99 and east of the San Joaquin River. The dairies with deep water table are all located in Tulare and Kings County. Water table depth had a statistically significant control on nitrate-N, ammonium-N, and EC levels: Higher levels of all analytes were observed at the dairies with the shallow water table. However, the differences were most pronounced at "upgradient", "corral", and "lagoon" sites. In contrast, the average log-10 site median nitrate-N, total-N, and EC levels do not differ between the shallow and the deep "field" sites subject to manure applications.

It appears that the "lagoon" sites located in Tulare and Kings County (deep water table) are generally not subject to the high ammonium-N levels observed at the shallow sites in the northern San Joaquin Valley, even if the lagoons have been in place for several decades (four lagoon sites). While drilling continuous cores during the monitoring well construction at some of the deep water table sites, we did encounter thin perched water table (less than 1 m of saturation) at two lagoon sites at depth less than 10 m. However, monitoring wells constructed into the perched water table did not yield water samples at later dates. Water quality at these (temporarily) perched locations exhibited elevated ammonium-N concentrations of similar magnitude as at dairies with shallow water table. This indicates that lagoons at deep water table sites likely leach manure, but in contrast to lagoons at shallow water table sites, the ammonium-N leached is either subject to nitrification-denitrification or a lateral dispersal process within the unsaturated zone prevents leachate from reaching the monitoring wells. Some of the lagoon well sites with deep water table indeed show high salinity levels, but not consistently across the dataset.

The "corral" sites have significantly different effects on groundwater quality between deep and shallow water table sites. Since leaching rates from the corral are considered to be relatively small, we here consider specifically three deep water table sites at two old corrals (each more than 50 years in operation), all equipped with nested monitoring wells. Salinity levels at the three sites are similar or higher in the uppermost saturated well interval when compared to those below and comparable to that found at the shallow dairy sites. However, they are not higher than in nearby sites classified as "field". Nitrate-N levels that are much lower than in nearby "field" sites, indicate potentially significant nitrification-denitrificiation of ammonium-N percolating at the corral site.

Importantly, “field” sites on five dairies with deep water table appear to have a similar magnitude and variability of nitrate-N as those at two dairies with shallow water table sites. At “field” sites, denitrification or other dilution mechanisms appear to play at most a limited role. VanderSchans et al. (2009) indicated that the nitrogen mass balance at field sites is a significant factor determining the leaching of nitrate to groundwater and the nitrate concentration found in first encountered groundwater at these sites.

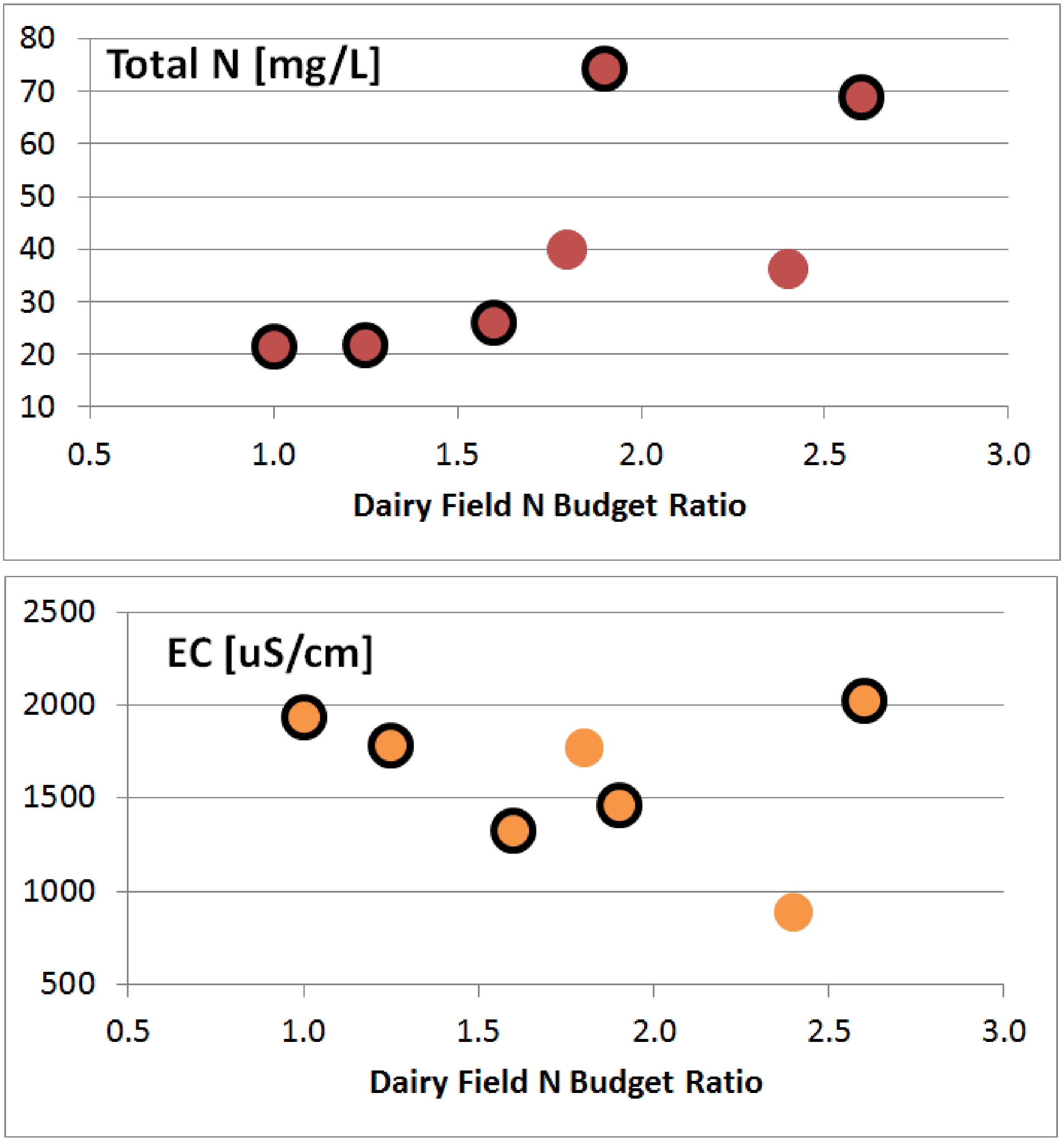
For the dairies investigated, we developed an average field N mass balance to determine whether there is a correlation between the field N mass balance and nitrate concentration in “fields”. The mass balance is based on the reported acreage and harvested nitrogen of field crops receiving manure, not including alfalfa, the amount of excreted manure, of which 70% is assumed to be land-applied, the amount of nitrate applied with irrigation water, the amount of nitrogen in atmospheric deposition, the reported amount of synthetic fertilizer application, and the reported amount of nitrogen exports from the farm. Reported data were obtained from interviews with the operators and from the 2007 and 2008 annual reports submitted to the Central Valley Regional Water Board.

Here, we specifically compared the ratio of total field applied N to harvested N (“dairy field N budget ratio”) to the average of median site total N and EC observed at each dairy (Figure 4). Considering only older dairies, larger dairy field N budget ratios lead to higher mean (of site median) total nitrogen in groundwater. Dairies with a field N budget ratio of 1.6 and lower have mean total nitrogen concentrations of 20 – 30 mg N/L. The two older dairies with large ratios have much higher total N concentrations. In contrast, one of the two new dairies has a much lower mean total N concentrations than the older dairies with similarly high field N budget ratios. The total N value for 36-11 (which exhibits the highest value) is possibly influenced by nearby septic leach fields and may be an outlier.

For salinity (EC), there is no apparent relationship between salinity in groundwater below fields and the dairy field N budget ratio. This may be due to the large variability in natural groundwater salinity. Particularly at dairies 36-15 and 36-19, with very low ratios, the EC values are high, possibly due to natural conditions.

The relationship between “field” total nitrogen and the N budget ratio is not statistically significant, since four of the seven dairies have only 1 “field” well site, which cannot be considered representative. However, at dairies with multiple “field” well sites, which here are those with the lowest dairy field N budget ratio, well sites generally exhibit the lower concentration, when compared to the other dairies. To obtain stronger statistical support, this type of analysis will require a larger population sample to develop a statistically more meaningful analysis between field nitrogen budgets and groundwater nitrate.

Figure 4: Dairy-specific average median site total N [mg/L] and electrical conductivity (EC) [uS/cm] at "field" monitoring sites as a function of the dairy-specific ratio of total field applied N to total harvested N ("dairy field N budget ratio"). Circled symbols represent the 5 older dairies, uncircled symbols represent the 2 new dairies. Dairies from left to right: 36-15, 36-19, 37-42, 36-27, 36-11, 36-04, 37-39. The number of well sites are 3, 2, 5, 1, 1, 1,and 1, respectively (see Table 1).



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