Identifying Sources of Groundwater Nitrate Contamination in a Large Alluvial Groundwater Basin with Highly Diversified Intensive Agricultural Production

Task Report 3

Project

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

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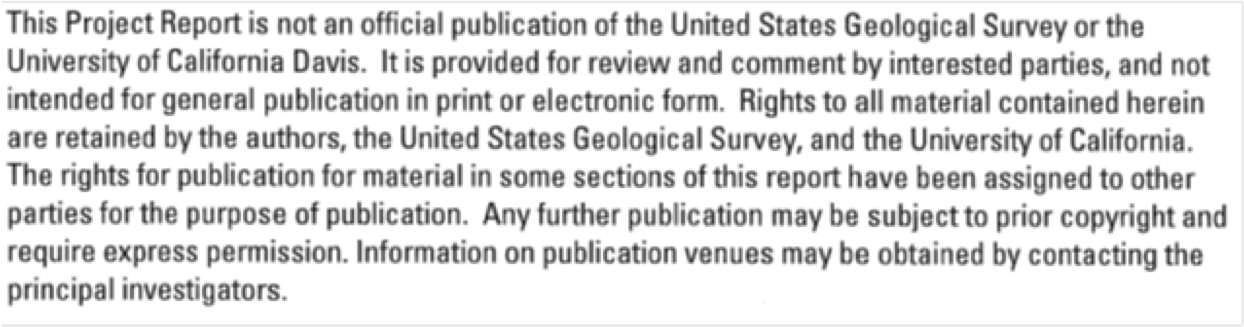

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Abstract

Groundwater quality is a concern in alluvial aquifers underlying agricultural areas worldwide. Nitrate from land applied fertilizers or from animal waste can leach to groundwater and contaminate drinking water re- sources. The San Joaquin Valley, California, is an example of an agricultural landscape with a large diversity of field, vegetable, tree, nut, and citrus crops, but also confined animal feeding operations (CAFOs, here mostly dairies) that generate, store, and land apply large amounts of liquid manure. As in other such regions around the world, the rural population in the San Joaquin Valley relies almost exclusively on shallow domestic wells (≤ 150 m deep), of which many have been affected by nitrate. Variability in crops, soil type, and depth to groundwater contribute to large variability in nitrate occurrence across the underlying aquifer system. The role of these factors in controlling groundwater nitrate contamination levels is examined. Two hundred domestic wells were sampled in two sub-regions of the San Joaquin Valley, Stanislaus and Merced (Stan/Mer) and Tulare and Kings (Tul/Kings) Counties. Forty six percent of well water samples in Tul/Kings and 42% of well water samples in Stan/Mer exceeded the MCL for nitrate (10 mg/L NO3-N). For statistical analysis of nitrate contamination, 78 crop and landuse types were considered by grouping them into ten categories (CAFO, citrus, deciduous fruits and nuts, field crops, forage, native, pasture, truck crops, urban, and vineyards). Vadose zone thickness, soil type, well construction information, well proximity to dairies, and dominant landuse near the well were considered. In the Stan/Mer area, elevated nitrate levels in domestic wells most strongly correlate with the combination of very shallow (≤ 21 m) water table and the presence of either CAFO derived animal waste applications or deciduous fruit and nut crops (synthetic fertilizer applications). In Tulare County, statistical data indicate that elevated nitrate levels in domestic well water are most strongly associated with citrus orchards when located in areas with a very shallow (≤ 21 m) water table. Kings County had relatively few nitrate MCL exceedances in domestic wells, probably due to the deeper water table in Kings County.

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

1. Introduction

Elevated nitrate levels (more than 2 mg/L NO_3-N) in groundwater used as drinking water have been linked to adverse health effects (Mueller and Helsel, 1996, et al.). Consumption of water containing elevated levels of nitrate can cause low blood oxygen in infants, a condition known as methemoglobinemia or "blue baby syndrome". Methemoglobinemia was the impetus behind the United States Environmental Protection Agency (USEPA) maximum contamination level (MCL) of 10 mg/L NO_3-N (Mueller and Helsel, 1996). Nitrate in drinking water has also been linked to cancer through the formation of carcinogenic N-nitroso compounds (Weyer et al., 2001), to spontaneous abortions (Centers for Disease Control and Prevention, 1996), and to non-Hodgkin's lymphoma (Ward et al., 1996).

Nitrate occurs naturally in groundwater. However, septic leakage, nitrogen fertilizers, and animal manure applied to soil can cause elevated levels of nitrate in groundwater (Owens et al., 1992). High groundwater nitrate has been positively correlated with surrounding agricultural landuse (Vowinkel and Tapper, 1995). In the San Joaquin Valley (SJV) (Figure 1) as much as 88 kg N/ha/year may leach to groundwater in areas where fertilizers are applied (Harter, 2009). Leaching from dairy corrals, ponds, and from fields receiving manure may be as high as 872 kg/ha/year, 807 kg/ha/year and 486 kg/ha/year, respectively (van der Schans et al., 2009). Increasing trends in nitrate levels in SJV groundwater during the 1950s and 1960s and from the 1970s to 1980s correlated with an increase in fertilizer and manure use, and an increase in confined animal feeding operations (CAFOs) in the SJV over the same time period (Dubrovsky et al., 1998).

Approximately two-thirds of the SJV landscape is in agricultural production (Burow et al., 2008). More than 250 unique crops are grown in the SJV. It is home to three-quarters of California's dairy herd. The annual gross value of agricultural production in the SJV is more than $25 billion (United States Environmental Protection Agency, 2012). Irrigation water is supplied by both surface water and groundwater, while ground- water is the almost exclusive source of drinking water in rural and embedded urban areas such as Stockton, Modesto, Fresno, Tulare, and Bakersfield (Burow et al., 1998b). Total population for the eight counties in the SJV (Fresno, San Joaquin, Kern, Stanislaus, Tulare, Merced, Kings, and Madera) in 2006 was nearly 3.9 million (California Department of Finance, 2006).

Nitrate contamination of shallow groundwater (≤ 150 m deep) in the SJV is well documented. Twenty groundwater study units, distributed throughout the nation, were compared as a part of the U.S Geological Survey (USGS) National Water Quality Assessment Program (NAWQA). Among the twenty NAWQA study units, the SJV (also referred to as the San Joaquin-Tulare Lake Basin) had nitrate concentrations in groundwater above the national median (Dubrovsky et al., 1998). The 2006 California State Water Resources Control Board (SWRCB) Groundwater Ambient Monitoring and Assessment Program (GAMA) study of 181 domestic wells in Tulare County (including wells located in the foothills outside the SJV) found 40% of well water samples exceeded the nitrate MCL (California State Water Resources Control Board, 2010). A similar study conducted in Merced County in 2001 on 40 domestic wells found 63% to exceed the MCL for nitrate (Harter and Romesser, 2001).

Previous studies conducted in agricultural areas overlying unconsolidated aquifers determined a significant relationship between crop type or landuse within circular well buffer zones centered on sampled wells and well water nitrate (Burow et al., 1998a; McLay et al., 2001; Kolpin, 1996). However, previous studies, typically including 50 to 100 well sites, have been limited to relatively few crop type and landuse classifications (Burow et al., 1998a; McLay et al., 2001) or overarching categories such as "irrigated agriculture" (Kolpin, 1996). Studies have also shown that nitrate in groundwater can be affected by vadose zone thickness (Burow et al., 1998b) and soil type (Burow et al., 1998a) and that nitrate in well water samples can be affected by well construction characteristics such as well depth (Burow et al., 1998b).

This study expands on previous work using a larger sample size across a wider diversity of agricultural crops and landuses. The goal of this study is to determine how various landuses affect groundwater nitrate and how other factors, such as well depth, may play a role in the amount of nitrate found in well water samples. Specifically, we consider 78 crop and landuse types (grouped into 10 categories), proximity to dairies, vadose zone thickness, soil type, and well construction characteristics.

2. Methods

2.1 Project Area Description

The study area is located in the San Joaquin Valley (SJV), which represents the southern portion of the Great Central Valley of California. The SJV is a structural trough up to 322 km (200 miles) long and 113 km (70 miles) wide (DWR, 2004) that is filled with up to 10 km (6 miles) of marine and continental sediments (Page, 1985) deposited by the Pacific Ocean and erosion of the surrounding mountains. Fresh groundwater is found in tertiary and quaternary alluvial sediments comprising the upper 500 to 1000 meters of sediments (DWR, 2004). The SJV is bounded to the east by the Sierra Nevada Mountains, to the west by the Coast Ranges, to the south by the San Emigdio and Tehachapi Mountains, and to the north by the Sacramento-San Joaquin Delta (DWR, 2004). The SJV contains the San Joaquin Groundwater Basin (the northern section) and the Tulare Ground- water Basin (the southern section) (Gronberg et al., 1998).

Domestic wells were sampled in Stanislaus, Merced, Tulare, and Kings Counties. To compare an area with more shallow groundwater and more sandy soils with an area of deeper groundwater and more clayey soils, the project area is divided into two separate regions: 1) the valley floor area of Stanislaus and Merced Counties (Stan/Mer) and 2) the valley floor area of Tulare and Kings Counties (Tul/Kings) (Figure 1). The Stanislaus and Merced Counties (Stan/Mer) project area is approximately 0.55 million hectares (1.35 million acres). Surface geologic units in Stan/Mer consist of unconsolidated sand, gravel, and silt with percolation rates of very rapid (> 25 cm/hr) to very slow (<0.13 cm/hr) (Burow et al., 2004). From Spring 2000 measurements, depth to groundwater near the Sierra foothills in Stanislaus and Merced Counties was approximately 30 m (100 feet) below ground surface (bgs) and decreased in a southwesterly direction to less than 3 m (10 feet) bgs along the San Joaquin River (Figure 1 and (Kretsinger et al., 2010)). The Tulare and Kings Counties (Tul/Kings) project area is approximately 0.66 million hectares (1.64 million acres). Sur- face geologic units in Tul/Kings consist of unconsolidated silt, clay, and fine sand and are poorly permeable to highly permeable (Croft and Gordon, 1968). The Spring 2000 depth to groundwater in Tulare County generally increased from 3-6 m (10-20 feet) bgs in the east to over 49 m (160 feet) bgs in western Tulare County and Kings County (Figure 1) (Kretsinger et al., 2010).

2.2 Sample Distribution

Two hundred samples were collected from domestic wells within the two project areas. Domestic wells were located at homes, dairies, or (in only several cases) as part of a public water system. One hundred samples were collected in the Stan/Mer project area (with groups of samples concentrated around Hilmar, Delhi, Atwater, Merced, Le Grand and Los Banos) (Figure 2). One hundred samples were collected in the Tul/Kings project area, with groups of sampled wells concentrated around

Hanford, Lemoore, and Porterville (Figure 2). Wells were chosen based on the response of property owners to newspaper ads and flyers mailed to rural residents. Thus, our well distribution was limited by the willingness of property owners to participate in our study and the distribution of existing wells. The California State Water Resources Control Board (SWRCB) was also limited by volunteer responses to mailed flyers in selecting domestic wells for their 2006 GAMA domestic well study in Tulare County for which 1,500 flyers were mailed and 181 people volunteered to have their well tested (California State Water Resources Control Board, 2010). We observed a similar response rate to our mailed flyers and sampled al- most all volunteered wells. We were not able to target wells with particular surrounding landuse.

2.3 Sample Collection and Analysis

Samples were collected between Spring 2010 and Summer 2011. Each well was sampled only once. Previously, no significant seasonal variation was found in nitrate in groundwater sampled every 5-6 weeks for four years (1995-1999) from monitoring wells on five SJV dairies (Harter et al., 2002). In this region, recharge to groundwater is from both summer irrigation and winter rain. Recharge does not have strong seasonal variations in low to normal rainfall years, but can be higher in spring months of wet years (Ruud et al., 2004). In domestic wells of the two study areas, significant seasonal variations of nitrate in groundwater were not expected due to the relative constancy of recharge, due to mixing and dispersion in the vadose zone, and perhaps most importantly due to mixing of groundwater of varying age along the domestic well screen (Horn and Harter, 2009).

All water samples were collected from spigots outside of the home or dairy facility. When a water storage tank was present at the well, samples were collected from spigots before the tank when possible (32 wells in Stan/Mer and 21 wells in Tul/Kings). When the wellhead was inaccessible or a spigot was not present between the tank and the wellhead, the sample was collected at the closest accessible spigot to the wellhead. Two samples in Stan/Mer were collected after a filter. Approximately 57 liters (15 gallons) were purged from each well before sample collection to clear out standing water in pipes. If water displayed a tint or odor, up to 380 liters (100 gallons) were purged until water cleared. Water storage tanks were not drained. After purging, the spigot was fitted with plastic tubing and water was filtered through a 0.45-micron filter and collected in a 250 ml clear plastic bottle. Date and time of collection were recorded as well as the precise latitude and longitude location of the well. Samples were kept cool in an ice chest while still in the field and then transported to UC Davis' cold room for storage before delivery to the UC Davis Analytical Lab for analysis. Samples were collected over a one year period and delivered to the lab approximately every 3 weeks. For quality control, field blanks and duplicates were collected approximately every 10 wells. Nitrate was not detected in any field blanks and average percent difference between sample and field duplicate was 0.5. Samples were analyzed for nitrate as NO_3-N by the Cadmium Reduction Flow Injection Method, Standard Method 4500-NO_3-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.

2.4 Landuse Analysis

Landuse analysis was performed using ESRI ArcGIS (Version 10) and the California Augmented Multisource Landcover Map (CAML) (Hollander, 2010) 50 m grid of landuse/landcover, which was reclassified into ten categories:

- Native,
- Urban,
- Citrus,
- Deciduous Fruits and Nuts,
- Forage,
- Field Crops,
- Pasture,
- CAFOs,
- Truck Crops (i.e., vegetables and berry crops), and
- Vineyards

See Appendix A for a list of original crop and landuse types included in each category. The ten landuse categories listed above were quantified in square meters (m^2) within a 2.4 km radius ("well buffer area") centered on each well. A circular region centered on each well was chosen because groundwater flow direction at each well site was unknown. In the absence of known groundwater flow direction, a circular region centered on each well reflects an unbiased estimate of the potential source area (Barringer et al., 1990). See Appendix B for justification on choice of the 2.4 km radius.

Since nitrate leaching into groundwater from dairy corrals and lagoons, or from manure applied to forage crops can be a major contributor to groundwater nitrate (van der Schans et al., 2009), well distance to a dairy CAFO was also considered. To test possible CAFO derived animal waste contributions to groundwater nitrate, wells were given a "dairy" or "non- dairy" designation depending on the distance to the nearest dairy corral or lagoon. Latitude and longitude locations were used to determine each well's distance to a dairy corral or lagoon. Dairy corral and lagoon polygons were digitized from the United States Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP) 2009 aerial imagery (United States Department of Agriculture, 2009). Wells located within a 2.4 km radius from a dairy corral or lagoon were considered "dairy wells", otherwise, they were considered "non-dairy" wells.

2.5. Other Information

Well construction information was assembled from well construction logs or from information provided by landowners. A well construction log or depth information supplied by the landowner was available for 49 wells (49%) in the Stan/Mer project area and for 42 wells (42%) in the Tul/Kings project area. Screened interval length was available for 42 wells (42%) in the Stan/Mer project area and for 38 wells (38%) in the Tul/Kings project area. Although well construction information was not available for every well, we expect that the available data is an accurate representation of the wells in the area.

Groundwater depth and general soil type was collected with information provided by the California Department of Pesticide Regulation (CDPR). CDPR has modeled groundwater, soil, and pesticide detections to define Groundwater Protection Areas (GWPAs). GWPAs are 2.60 km^2 (1 $mile^2$) zones that are sensitive to the movement of pesticides leading to pesticide use restrictions in these zones (DPR, 2011). A GWPA has one or more of the following characteristics:

- Previous detections of pesticides in that section, or

- Contains coarse soils and depth to groundwater < 21 m (70 feet) (leaching zones), or

- Contains runoff-prone soils or hardpans and depth to groundwater < 21 m (70 feet) (runoff zones) (DPR, 2011).

GIS shapefiles of CDPR GWPA zones were used to determine if a well was located within a GWPA. Within a GWPA, wells were assigned a categorical descriptor for depth to groundwater < 21 m (70 feet). Outside a GWPA wells were assigned depth to groundwater > 21 m (70 feet). Wells within GWPAs were assumed to be dominated by soil type “leaching” or “runoff” depending on the GWPA designation (Figure 2).

2.6. Statistical Methods

Non-parametric statistical tests were used because nitrate data collected in this study were not normally distributed and some of the sample groups were small. Groups were also not balanced, that is, group size may be dissimilar. Similar right skewed nitrate distribution was found between groups (Figure 3). The Spearman’s Rank Correlation (SRC) was used to determine the correlation between two continuous variables (Conover, 1999), such as nitrate concentration in well water samples and distance to a dairy corral or lagoon. SRC calculates a correlation coefficient (ρ) by assigning an integer rank to each variable and comparing the ranks (a ρ of 1 indicates perfect correlation) (Zar, 2005). The Mann-Whitney test was used to determine if there was a difference between two groups of data (Conover, 1999) such as nitrate level in well water samples from dairy wells versus non-dairy wells. The Kruskal-Wallis test was used to deter- mine if there is a significant difference between three or more groups of data (Siegel and Castellan, 1988). The significance level used for all statistical tests was 95% (or $\alpha=0.05$).

Multivariate analysis was not considered in this paper. The analysis performed here is for data exploration purposes with the intent of using the results to aid future multivariate techniques.

3. Results and Discussion

3.1. Well Depths and Screen Lengths

In Stan/Mer, screen length for the sampled wells has a mean of 11 m and a median of 6 m and completed well depth has a mean of 55 m and a median of 55 m. In Tul/Kings, screen length for the sampled wells has a mean of 27 m and a median of 20 m and completed well depth has a mean of 73 m and a median of 61 m (Figure 4). In general, wells sampled in Tul/Kings have longer screened intervals and were deeper than wells sampled in Stan/Mer.

When compared using the SRC, the study wells did not have a significant relationship between depth to top of well screen, depth to middle of well screen, or screen length and nitrate level in either Stan/Mer or Tul/Kings. However, nitrate levels did significantly decrease as completed well depth increased within Stan/Mer wells ($p=0.028$ and $\rho=-0.315$), but not for Tul/Kings wells (Figure 5).

In a 1995 USGS study of 30 domestic wells scattered throughout the eastern SJV, from Bakersfield to Sacramento, nitrate levels were found to significantly decrease with increasing depth to top or middle of screened intervals (Burow et al., 1998b). This was consistent with a significant decrease in nitrate with increasing well depth found when Stan/Mer and Tul/Kings datasets were combined. These findings indicate an overall regional trend of lower nitrate levels with depth ($p=0.0405$ and $\rho=-0.215$). However, as indicated by the Tul/Kings area, subregionally such trends may not always occur due to reduced strength of nitrate sources in more recent recharge, the influence of surface water recharge, subsurface heterogeneity and attenuation, or other factors.

3.2. Nitrate Exceedance Rates

Background nitrate levels in groundwater are typically less than 2 mg/L NO_3-N (Mueller and Helsel, 1996; Harter, 2009). Elsewhere, nitrate levels of 4 mg/L or greater have been used as a threshold to demonstrate anthropogenic effects (Nolan et al., 2002). Here, we adopted 2 mg/L as the threshold for background nitrate levels. Then, half of the nitrate MCL (or 5 mg/L) and the nitrate MCL (10 mg/L) were chosen as the next two threshold levels. Therefore, domestic well sample results for nitrate as NO_3-N were grouped into four categories: 1) ≤ 2 mg/L, 2) > 2 mg/L and ≤ 5 mg/L, 3) > 5 and ≤ 10 mg/L and, 4) > 10 mg/L. For data analysis, non-detect nitrate results were replaced with 0.025 mg/L NO_3-N, one half the detection limit of 0.05 mg/L NO_3-N (Helsel, 2005).

A considerable percentage of wells in both project areas had elevated nitrate levels. In Stan/Mer, 33% of wells had nitrate that was elevated but below the MCL (> 2 mg/L and ≤ 10 mg/L) and 42% of wells exceeded the MCL (Figure 2 and Table 1). MCL exceedances seem to be concentrated in the Hilmar and Delhi area (Figure 2). In Tul/Kings, 33% of wells had nitrate that was elevated but below the MCL (> 2 mg/L and ≤ 10 mg/L) and 46% of wells exceeded the MCL (Figure 2 and Table 1). These findings are consistent with the findings of the 2006 GAMA study conducted by the SWRCB that found 44% of 136 domestic wells sampled on the valley floor in Tulare County exceeded the MCL (California State Water Re- sources Control Board, 2010) (136 out of 181 wells sampled in the GAMA study were on the valley floor, GAMA wells located in the foothills were not considered here). MCL exceedances seemed to be most common along the eastern valley margin of Tulare County, while background levels were more common west of Hanford in Kings County (Figure 2). Overall median nitrate among the 200 wells was 8.7 mg/L NO_3-N, just below the MCL of 10 mg/L.

The median and the exceedance rates were higher than the median of 4.6 mg/L NO_3-N and MCL exceedance rate of 17% found in the 1995 USGS study mentioned in the previous section (Burow et al., 1998b). For the 7 wells sampled by the USGS in 1995 in Stan/Mer, the median nitrate level was 4.8 mg/L with 1 out of 7 (14%) wells exceeding the nitrate MCL; the 1995 median nitrate value for the 9 wells in Tul/Kings sampled by the USGS was 5.4 mg/L with 2 out of 9 (22%) wells exceeding the nitrate MCL (Burow et al., 1998b) (compare to Table 2). Twenty-three of the 30 wells sampled in 1995 had also been sampled in 1986-87 as a part of the U.S. Geological Regional Aquifer System Analysis Program, at which time the median nitrate level was significantly lower at 2.4 mg/L NO_3-N (Burow et al., 1998b).

Other agricultural areas of the Unites States have similar MCL exceedance rates in wells. Well data collected in the 1980s from wells in the Delmarva Peninsula, Long Island, Connecticut, Kansas and Nebraska regions had 12-46% exceedance rates (Hamilton and Helsel, 1995).

The drinking water standard exceedance rates found in Stan/Mer and Tul/Kings are also within the range of exceedance rates found for other agriculturally intensive regions around the world. The North China Plain (NCP), central Japan, Bangladesh, and Cecina (Tuscany, Italy) are other alluvial aquifers underlying agriculturally intensive landuse where ground- water contamination of nitrate occurs. In 1993 and 1994, 57 irrigation or house wells (with average depth of 57 m) were tested throughout agricultural areas in fourteen NCP cities and counties. The study found 37 of 57 (63%) wells exceeded the current World Health Organization (WHO) drinking water standard of 11.3 mg/L NO_3-N. (Zhang et al., 1996; WHO, 2007). In contrast, a 1999 study conducted in Quzhou County (NCP) (ground- water depth ranging between 0.4 and 1.38 m) tested 139 wells and found only four wells (3%) exceeded the Chinese drinking water standard for nitrate (20 mg/L NO_3-N) (Hu et al., 2005). In Kakamigahara Heights (central Japan), 57 domestic, farm, monitoring and public supply wells were tested for nitrate in 1999 and 32% exceeded the Japanese drinking water standard for nitrate (9.9 mg/L NO_3-N) (Babiker et al., 2004). In a study conducted in Bangladesh, 80 groundwater samples were collected from existing domestic tube wells in early December 2005 found about 8% of samples exceeded the WHO standard for nitrate (Majumder et al., 2008). A study conducted in Cecina, Italy in May through June and September through October 1998 found 19% of 57 wells and 26% of 65 wells, respectively, exceeded the WHO drinking water standard for nitrate (Grassi et al., 2007).

3.3. Nitrate Comparison by Groups

Median nitrate values for wells in Stan/Mer and wells in Tul/Kings were not significantly different (Table 3 and Figure 6), despite differences in landuse, the distribution of dairies, and differences in soil or ground- water characteristics between these two subregions. Non-dairy wells in Tul/Kings had a significantly higher median nitrate value than non-dairy wells in Stan/Mer. In contrast, dairy wells in Tul/Kings had a significantly lower median nitrate value than Stan/Mer dairy wells.

Within the subregions, Tul/Kings wells designated as non-dairy had a significantly higher median nitrate value than wells designated as dairy, suggesting that a dairy within 2.4 km of the well is not associated with the highest nitrate levels in Tul/Kings. In contrast, Stan/Mer wells designated as dairy had a higher, but not significantly higher median nitrate value from wells designated as non-dairy. When no distinction between project areas was made and dairy and non-dairy wells were compared as a whole, dairy and non-dairy wells did not have significantly different median nitrate values, due to the opposing relationships of median nitrate values between dairy and non-dairy areas within these two subregions. These findings suggest that while both project areas have wells with high nitrate values, a dairy within 2.4 km of a well is not necessarily a clear indicator for higher nitrate values. A well may be within 2.4 km of a dairy, but depending on groundwater flow direction and hydraulic gradient, nitrate leaching from CAFO animal waste may or may not impact the well. The effect of dairies on nitrate levels in wells is likely controlled by additional factors such as groundwater recharge rate, soil type, groundwater age, and nutrient management practices.We sampled 72 Tulare County wells and these wells had a significantly greater median nitrate value than the 136 Tulare County wells tested in 2006 by the SWRCB GAMA study (California State Water Resources Control Board, 2010) (for this comparison we removed wells sampled in the GAMA study that were not on the valley floor). This finding may be evidence that domestic well nitrate levels in wells in Tulare County continue to increase. However, because the data are not taken from the same wells, the data do not permit a quantification of the increase.

In Stan/Mer, dairies are well distributed throughout the study area. The 2.4 km distance criterion to distinguish dairy region wells versus non- dairy wells may be considered too restrictive due to the generality of the underlying assumptions. Therefore, in addition to dairy as a categorical predictor variable, we also investigated the distance to a dairy corral or lagoon as a continuous predictor variable using the SRC. For Stan/Mer wells, nitrate increased significantly as well distance to dairy corral or lagoon decreased ($p=0.016$ and $\rho=-0.240$). In contrast to the categorical predictor variable, this statistical measure indicates that well proximity to a dairy is indeed a significant factor affecting groundwater nitrate levels in Stan/Mer. For Tul/Kings, the continuous predictor confirms the finding from the categorical analysis; nitrate level increased significantly as well distance to dairy corral or lagoon increased ($p=0.032$ and $\rho=0.215$). This is likely because non-dairy wells in Tul/Kings are mostly located on the eastern edge of the valley, where few dairies are located (Figure 7) and these non-dairy wells had significantly higher nitrate than the dairy wells (while also having a greater distance to dairy corral or lagoon).

3.4. Nitrate and Depth to Groundwater and Soil Type

CDPR maps of GWPA zones are shown in Figure 2. For wells in both project areas, wells located within a GWPA (n=103) had a median nitrate level of 12.2 mg/L NO3-N and wells not located within a GWPA (n=97) had a median nitrate level of 4.0 mg/L NO3-N. The medians were significantly different (p=2.85×10−8). The significantly higher median nitrate level for wells within GWPAs suggests that wells with depth to groundwater < 21 m (70 feet) are more likely to be impacted by high nitrate levels than wells with depth to groundwater > 21 m (70 feet).

Of the 103 wells within a GWPA, 54 wells are within a leaching GWPA and 49 are within a runoff GWPA (two runoff or leaching zones were classified as leaching zones for the purpose of this study). Leaching zone wells had a median nitrate value of 13.8 mg/L NO3-N and runoff zone wells had a median nitrate value of 10.7 mg/L NO3-N. The median nitrate levels of leaching zone versus runoff zone wells were not significantly different. GWPA wells located in Stan/Mer (n=56) had a median nitrate value of 12.8 mg/L NO3-N and GWPA wells located in Tul/Kings (n=47) had a median nitrate value of 11.4 mg/L NO3-N and these two medians were not statistically different. Since no significant difference was found for nitrate in wells between leaching or runoff classifications, we can assume that for wells with depth to groundwater < 21 m (70 feet) (very shallow groundwater), either soil type is vulnerable to elevated nitrate leaching.

In the Stan/Mer project area, CDPR GWPAs are mostly designated as leaching. The GWPAs are grouped throughout the areas where wells were sampled and MCL exceedances for nitrate are common throughout these areas (Figure 2). These areas are susceptible to contamination through landuse activities due to the very shallow water table. Stan/Mer had some of the highest nitrate values measured in this study, especially in the Hilmar area where the highest individual nitrate levels for this study were seen (including one > 60 mg/L for a well 6.10 m deep).

Within the Tul/Kings project area, elevated nitrate in groundwater seems mostly contained to Tulare County (Figure 2). Within Tulare County, MCL exceedances seem to be the most common east of Highway 99 and west of the foothills (Figure 2). The majority of CDPR GWPAs are located within this same area and are classified as runoff zones with depth to groundwater < 21 m (70 feet). Very shallow groundwater located within these GWPA zones is likely affected by overlying landuse through forced groundwater recharge of field runoff by ponding basins or dry wells.

Kings County has relatively few CDPR designated GWPAs. Kings County well water samples with relatively low nitrate levels (the majority less than 2 mg/L) are probably due to the deeper water table in Kings County (approximately > 21 m, or 70 feet).

3.5. Nearest Neighbor Analysis

Wells close together (within 5 km or 3 miles of each other) do not tend to have similar nitrate values. Figure 8 is a scatterplot of distance between nearest neighbor well pairs and absolute difference in their nitrate value. With the SRC test, we did not find a significant correlation between these two variables. In other words, if a well has a high nitrate value, the closest neighboring well in our sample set will not necessarily have a high nitrate level and vice versa. Nitrate level in wells depends on well depth, depth to groundwater, and likely, local groundwater flow direction and hydraulic gradient.

3.6. Nitrate and Landuse

Groundwater flow direction at each well is highly variable due to local pumping from numerous surrounding wells and is impossible to deter- mine without installing observation wells at each well site. The actual well source area for each well corresponds to less than 1% of the circular well buffer area created by the 2.4 km (1.5 mi) radius around each well (see Appendix B). The most likely landuse within the well buffer zone to affect water quality in a domestic well is the landuse category with the highest fraction ("dominant landuse"). On average, the dominant landuse comprised 51% of the well buffer area, but ranged from 25% to 85% in individual well buffer zones. We investigate the statistical relationship be- tween nitrate concentration and dominant landuse at each well. While this method ignores some potentially contributing landuses, it provides a statistical measure of potential landuse impact. Table 4 shows the distribution of dominant landuses among all 200 wells.

For statistical analysis, only dominant landuse categories occurring in at least 10 well buffer zones were considered (citrus, deciduous fruits and nuts, forage, native, and urban). The Kruskal-Wallis test was used to determine that median nitrate for wells grouped by dominant landuse are significantly different (p-value= 0.006, Figure 9). To determine significant differences between pairs of well groups, Mann-Whitney tests were per- formed (Table 5). Post-hoc tests that analyze the pairs all at once were not useful here because of the large relative differences in group sizes.

Wells with citrus or urban landuse as dominant landuse have median nitrate values above the drinking water limit of 10 mg/L. High nitrate in citrus areas is likely due to fertilizer, as citrus has historically used high fertilizer rates and is located on relatively permeable soils. The high nitrate in wells near "urban" areas may be the result of high septic systems density in peri-urban areas. Elevated median nitrate values close to, but not above the drinking water limit are associated with wells surrounded predominantly by deciduous fruit and nut crops (9.3 mg/L) or by forage crops (7.5 mg/L). Nuts and some deciduous fruits have relatively high nitrogen uptake rates and are subject to intensive fertilization. Forage crop acreage is the most likely to receive dairy manure applications.

Median nitrate levels are significantly higher in wells dominated by citrus than in wells dominated by fruit-and-nut crops, forage crops, or native lands. Median nitrate in wells surrounded predominantly by fruit- and-nut crops or by forage crops, in turn, are significantly higher than those in wells surrounded by predominantly native vegetation. Contrasts between other groups of wells are not statistically significant.

Stan/Mer and Tul/Kings have different landuse patterns. We investigated, whether dominant landuse influence on median nitrate are affected by the different patterns in these two regions. In

Stan/Mer, the landuse categories dominating total well buffer areas are deciduous fruits and nuts, forage, and urban , with 33%, 30%, and 9% respectively (Table 6). In Stan/Mer, deciduous fruit and nut crops are generally intermixed with forage, but deciduous fruit and nuts are more concentrated on the east side of the valley while forage crops are more concentrated on the west side; urban landuse is clustered near urban centers (Figure 7). Dairies are scattered throughout the two counties, but most densely located in the area between the San Joaquin River, Hwy. 99, the Stanislaus River, and the Merced River (Kretsinger et al., 2010). Forage crops are clustered around dairies.

The dominant landuses in total well buffer areas for Tul/Kings are for- age crops, citrus crops, and deciduous fruit and nut crops with 24%, 19%, and 16%, respectively (Table 6). Citrus is concentrated along the eastern edge of the valley in Tulare County. Other landuses are intermixed (Figure 7). In contrast to Stan/Mer, Tul/Kings has a much greater percent of landuse as citrus within well buffers (19% compared to 0.01%). Dairies in Tul/Kings are mainly located west of Highway 65 (west of the citrus landuse). Almost no dairies are located east of Highway 65. As with Stan/Mer, forage crops in Tul/Kings tend to surround CAFOs.

Dominant landuses in Stan/Mer with more than 10 wells were forage crops (44 wells, median NO_3-N = 9.9 mg/L) and deciduous fruit and nut crops (44 wells, median NO_3-N = 7.2 mg/L). These two groups were not statistically different. Both landuses appear to lead to elevated levels of nitrate in domestic wells with median values just below the drinking water threshold.

Dominant landuses in Tul/Kings (occurring in at least ten well buffer areas each) include citrus crops (27 wells, median NO_3-N = 11.4 mg/L), deciduous fruit and nut crops (19 wells, median NO_3-N = 7.8 mg/L), for- age crops (29 wells, median NO_3-N = 7.5 mg/L), and urban (13 wells, median NO_3-N = 10.7 mg/L). A Kruskal-Wallis test revealed that these groups were statistically different (p-value = 0.049). On this subset, nitrate in citrus dominated well areas was significantly higher than in wells near urban areas (p-value = 0.007), but other contrasts were not statistically significant. These other contrasts are only significant on the full dataset spanning both regions.

We also found that neither deciduous fruits and nuts nor forage yielded statistically significant differences in median nitrate concentration between Stan/Mer and Tul/King. The region therefore was not found to affect median nitrate values of these two groups.

A domestic well survey conducted by the USGS in 1992-1995 for wells in the eastern SJV also linked elevated nitrate levels to nearby fruit, nut, and vegetable crops. In the study, 60 domestic wells along the eastern SJV, with a mean depth of 45 m (150 feet), were sampled among three different agricultural landuse settings (Burow et al, 1998a). Twenty wells were sampled in each of the following landuse settings: almond; vineyard; and corn, alfalfa, and vegetable (Burow et al, 1998a). In this landuse study, Burow et al. found 30% of wells exceeded the nitrate MCL. Wells in the almond landuse setting had the highest nitrate levels (our deciduous fruits and nuts group includes almond orchards), followed by the corn, alfalfa, vegetable group (vegetables are equivalent to our truck crops group) and then the vineyard setting (medians of 10, 6.2, and 4.6 mg/L NO_3-N, respectively) (Burow et al, 1998a).

4. Conclusions

Overall, domestic wells in Stanislaus, Merced, and Tulare Counties (Kings County to a lesser extent) are widely affected by nitrate contamination above regulatory limits. That contamination is most strongly associated with CAFO manure lagoons and animal corrals and with forage, citrus and deciduous fruit and nut crops. Depth to groundwater provides significant control on nitrate concentration in domestic wells with higher values mostly where the water table is shallower < 21 m (70 feet) and lower nitrate values are found where the water table is deeper > 21 m (70 feet), regardless of soil type or dominant crop type. This compliments our finding that a more shallow well depth is related to a higher nitrate level. Wells close together (within 5 km or 3 miles of each other) do not have similar nitrate values probably because of the highly variable well construction characteristics from well to well and highly variable groundwater flow direction due to local pumping in large irrigation wells.

A dairy within 2.4 km of a well is not necessarily a clear indicator for higher nitrate values and the effect of dairies on nitrate levels in wells is likely controlled by additional factors such as groundwater flow direction, hydraulic gradient, depth to groundwater, nutrient management practices, groundwater travel time, and historical landuse practices. Our 2.4 km designation may be too limiting a measure to define “dairy” and “non-dairy” wells and perhaps cow and dairy density would be a more useful variable in future analysis. In addition, we analyzed distance to dairy corral or lagoon for correlation with nitrate level in wells (instead of the 2.4 km dairy or non-dairy cut off). We found significant, but opposing, relationships between nitrate level in wells and distance to dairy corral or lagoon (positively related for Stan/Mer and negatively related for Tul/Kings). This opposing relationship is probably due to the spatial distribution of other potentially high impact landuses or spatial variability in the additional factors listed above.

In Stan/Mer, our analysis suggests the dominant contributor to ground- water nitrate is CAFO derived animal waste leaching from lagoons and corrals in areas where dairies are densely located, fertilizers applied to deciduous fruit and nut crops, and CAFO derived animal waste applied to forage crops.

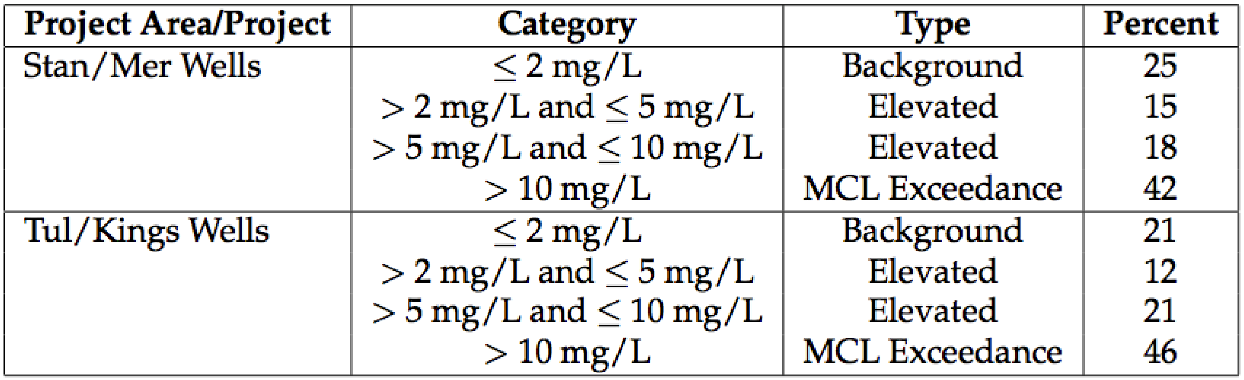
Out of all the well groupings compared, Tulare County wells had the highest median nitrate value (11.6 mg/L) and Tul/Kings non-dairy wells had the second highest median nitrate value (11.4 mg/L). The majority of Tul/Kings non-dairy wells were located east of Highway 65, where landuse is mainly citrus crops (Figure 7). Also, wells with dominant landuse as citrus crops had a median nitrate value of 11.4 mg/L. Our analysis suggests that elevated nitrate levels in well water samples in this area are likely due to a combination of very shallow water table and perhaps excessive nitrogen applications in citrus crops at the time of recharge. MCL exceedances and elevated nitrate levels were also common west of High- way 65, and east of Highway 99 in Tulare County (Figure 2). There, nitrate sources may be CAFO derived animal waste applied to forage crops, nitro- gen fertilizers applied to deciduous fruit and nut crops, and nitrogen from urban sources such as septic tanks. CAFO derived animal waste leaching from lagoons and corrals may contribute to groundwater nitrate in the areas where dairies are densely located, but because non-dairy wells in Tul/Kings had a significantly greater median nitrate value and are mostly located far from dairies (Figure 7), we cannot detect the influence of dairy corrals or lagoons near wells with the SRC test. By comparing to the results of the 2006 SWRCB GAMA study, we have demonstrated that nitrate values in wells in Tulare County may have increased since 2006.

Despite some contrasting results between the two study areas, the analysis showed that median nitrate values in wells with forage crops as dominant landuse were similar (not statistically different) between the two areas. The median nitrate values in wells with deciduous fruit and nut crops as dominant surrounding land use were also similar between the Stan/Mer and Tul/King areas, suggesting similar contamination processes. Not enough data were available to investigate whether such similarity in nitrate impact from the same dominating landuse holds for other crop categories.

Due to the depth of the wells, historic nutrient management practices and improvements potentially made to these practices must be considered in relating the results to current landuses. Also, spatial data on manured versus non-manured forage fields in all four counties would be valuable for future analysis. Analytes such as nitrate and water isotopes, ground- water age, and dissolved gasses in well water can provide clues about contamination sources, particularly animal versus synthetic nitrogen sources, and potential denitrification, work that is currently ongoing for the study area.

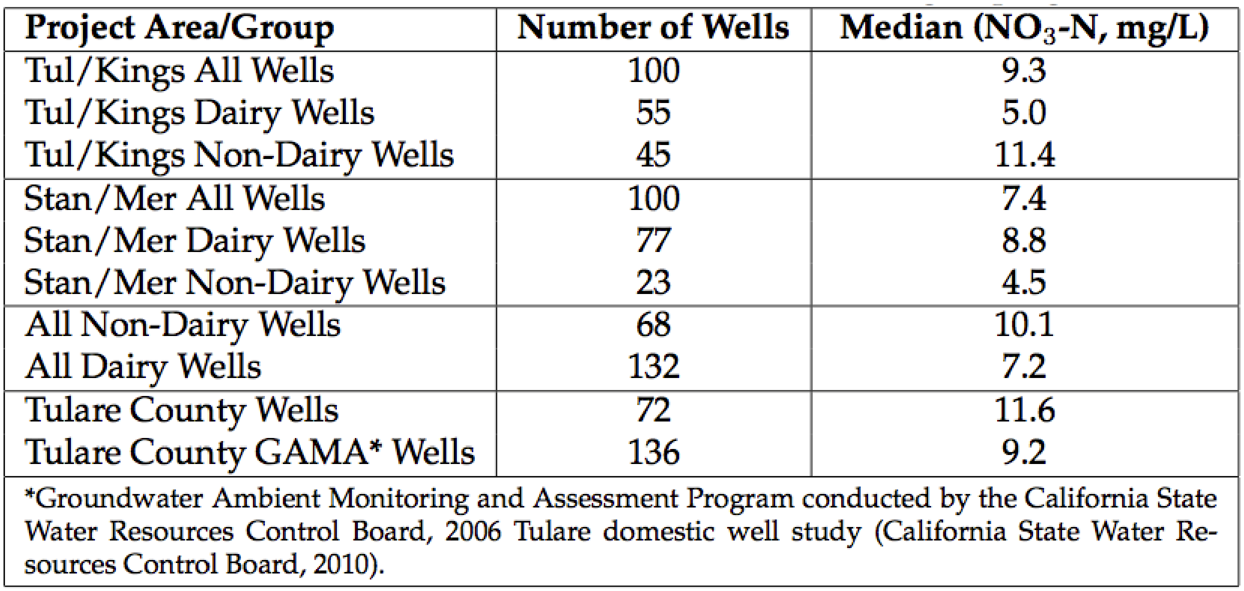
5. Tables

Table 1: Nitrate categories and percent of wells in each category.



Project Area/Project	Category	Type	Percent
Stan/Mer Wells	≤ 2 mg/L	Background	25
	> 2 mg/L and ≤ 5 mg/L	Elevated	15
	> 5 mg/L and ≤ 10 mg/L	Elevated	18
	> 10 mg/L	MCL Exceedance	42
Tul/Kings Wells	≤ 2 mg/L	Background	21
	> 2 mg/L and ≤ 5 mg/L	Elevated	12
	> 5 mg/L and ≤ 10 mg/L	Elevated	21
	> 10 mg/L	MCL Exceedance	46

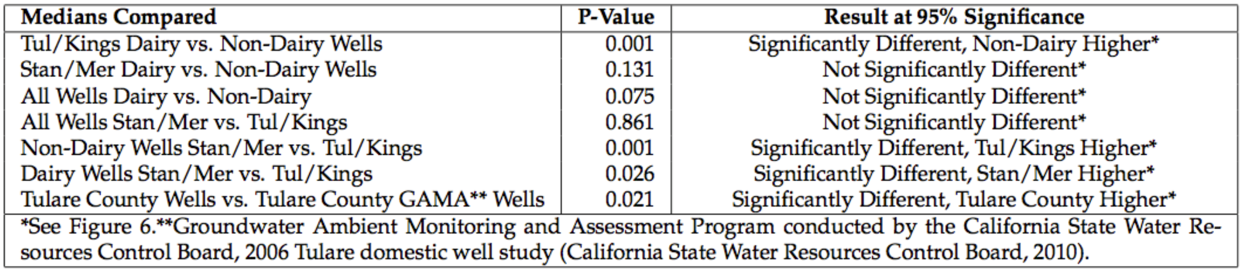
Table 2: Median nitrate value for wells in various groupings.



Project Area/Group	Number of Wells	Median (NO_3-N, mg/L)
Tul/Kings All Wells	100	9.3
Tul/Kings Dairy Wells	55	5.0
Tul/Kings Non-Dairy Wells	45	11.4
Stan/Mer All Wells	100	7.4
Stan/Mer Dairy Wells	77	8.8
Stan/Mer Non-Dairy Wells	23	4.5
All Non-Dairy Wells	68	10.1
All Dairy Wells	132	7.2
Tulare County Wells	72	11.6
Tulare County GAMA* Wells	136	9.2

*Groundwater Ambient Monitoring and Assessment Program conducted by the California State Water Resources Control Board, 2006 Tulare domestic well study (California State Water Resources Control Board, 2010).

Table 3: Mann-Whitney dairy versus non-dairy results.



Medians Compared	P-Value	Result at 95% Significance
Tul/Kings Dairy vs. Non-Dairy Wells	0.001	Significantly Different, Non-Dairy Higher*
Stan/Mer Dairy vs. Non-Dairy Wells	0.131	Not Significantly Different*
All Wells Dairy vs. Non-Dairy	0.075	Not Significantly Different*
All Wells Stan/Mer vs. Tul/Kings	0.861	Not Significantly Different*
Non-Dairy Wells Stan/Mer vs. Tul/Kings	0.001	Significantly Different, Tul/Kings Higher*
Dairy Wells Stan/Mer vs. Tul/Kings	0.026	Significantly Different, Stan/Mer Higher*
Tulare County Wells vs. Tulare County GAMA** Wells	0.021	Significantly Different, Tulare County Higher*

*See Figure 6.**Groundwater Ambient Monitoring and Assessment Program conducted by the California State Water Resources Control Board, 2006 Tulare domestic well study (California State Water Resources Control Board, 2010).

Table 4: Classification of wells by dominant landuse.

Category	Count	Median (NO_3-N, mg/L)
CAFO	0	-
Citrus	27	11.4
Deciduous Fruits and Nuts	63	9.3
Field Crops	6	0.0
Forage	73	7.5
Native	14	1.7
Pasture	1	1.7
Truck Crops	0	-
Urban	13	10.7
Vineyards	3	2.1

Table 5: Significant results for Mann-Whitney analysis for wells grouped by dominant landuse (non-significant pairs not shown).

Pair	p-value
Citrus-Forage	0.044
Citrus-Fruit and Nut	0.024
Citrus-Native	<0.001
Forage-Native	0.027
Fruit and Nut-Native	0.006

*Fruit and Nut refers to the deciduous fruits and nuts group.

Table 6: Landuse in total well buffer area for Stan/Mer and Tul/Kings, 0% means landuse was near zero when compared to the total.

Project Area	Native	Urban	Citrus	Deciduous Fruits and Nuts	Forage	Field Crops	Pasture	CAFOs	Truck Crops	Vineyards
Stan/Mer	7	9	0	33	30	4	5	3	4	4
Tul/Kings	10	12	19	16	24	11	2	1	0	5

6. Figures

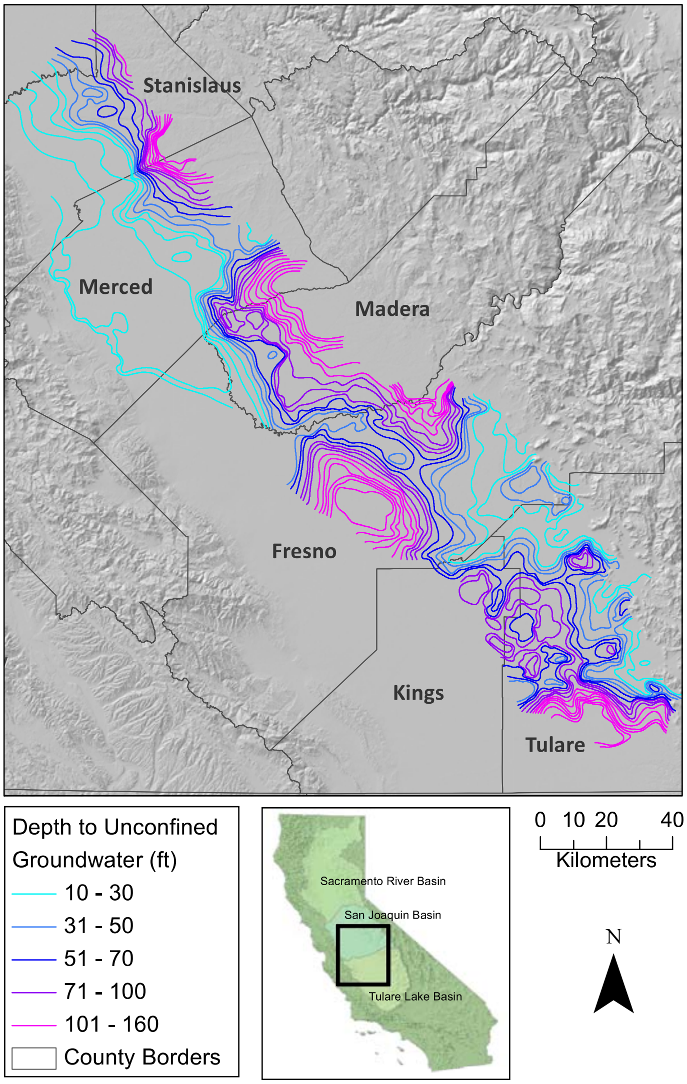


Figure 1: Stan/Mer and Tul/Kings study areas and DWR spring 2000 depth to unconfined aquifer in the San Joaquin Valley (1 ft = 0.3 m) (Department of Water Resources, 2011).

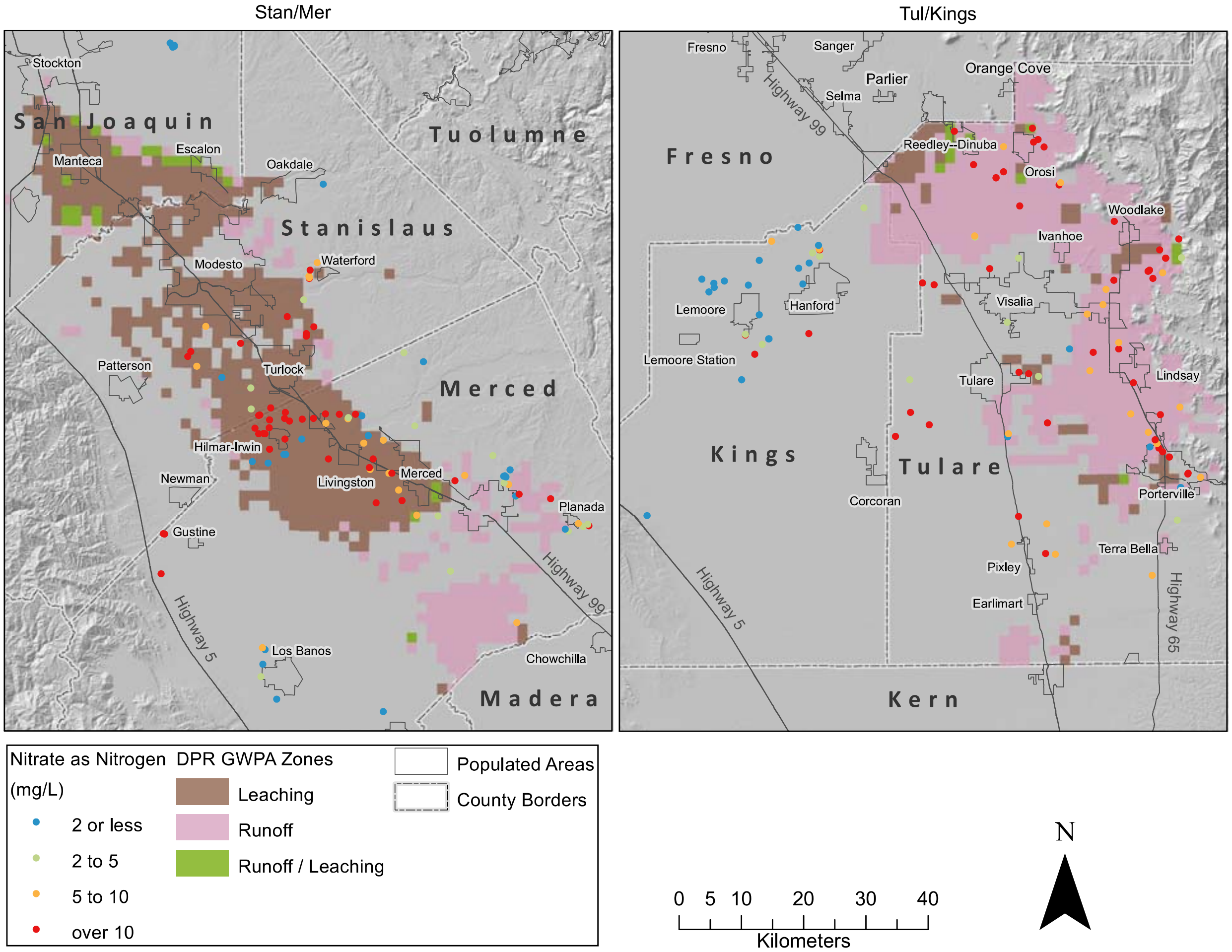


Figure 2: Sample locations color-coded by nitrate level and GWPAs (each square is 2.6 km^2 (1 mile^2) (DPR, 2011)) for Stan/Mer and Tul/Kings.

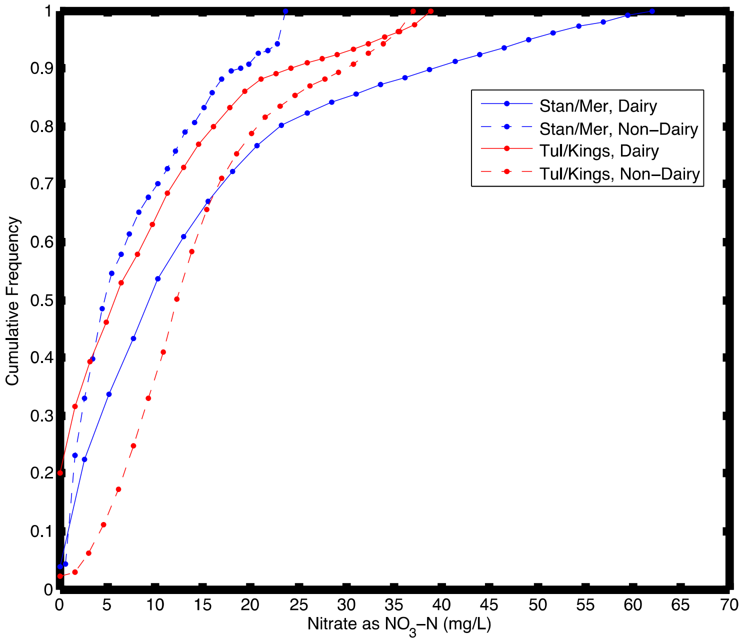


Figure 3: Distribution of nitrate for Stan/Mer and Tul/Kings dairy and non-dairy groups.

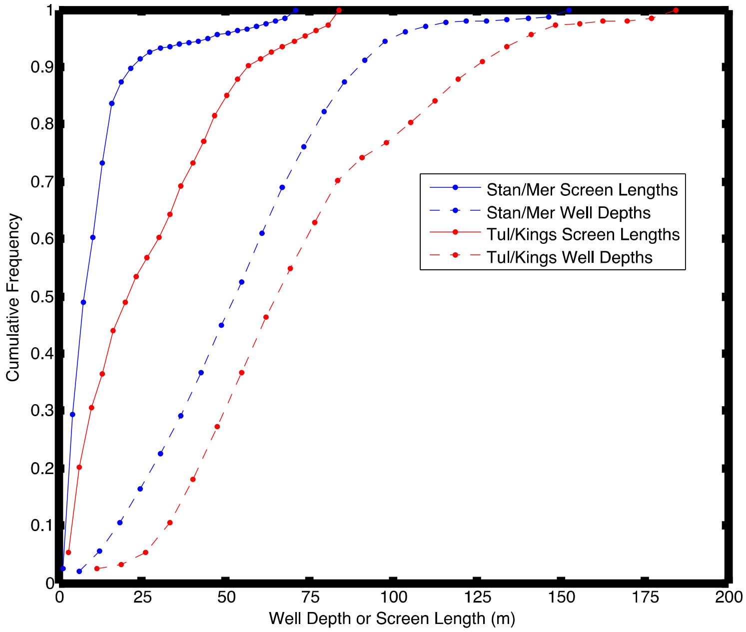


Figure 4: Distribution of well screened interval length and completed well depth for the Stan/Mer and Tul/Kings project areas.

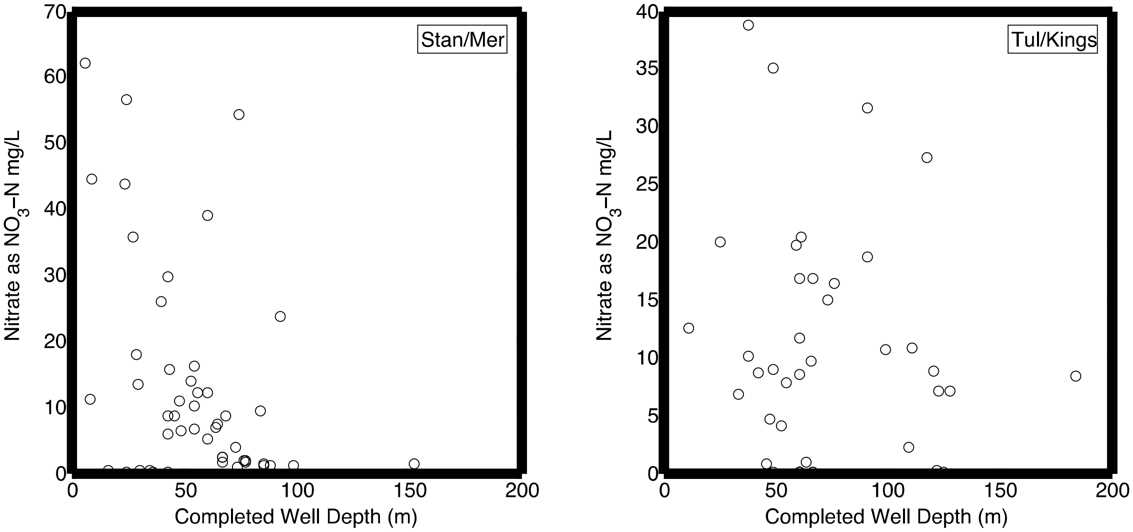


Figure 5: Scatter plots of nitrate versus completed well depth for Stan/Mer and Tul/Kings groups.

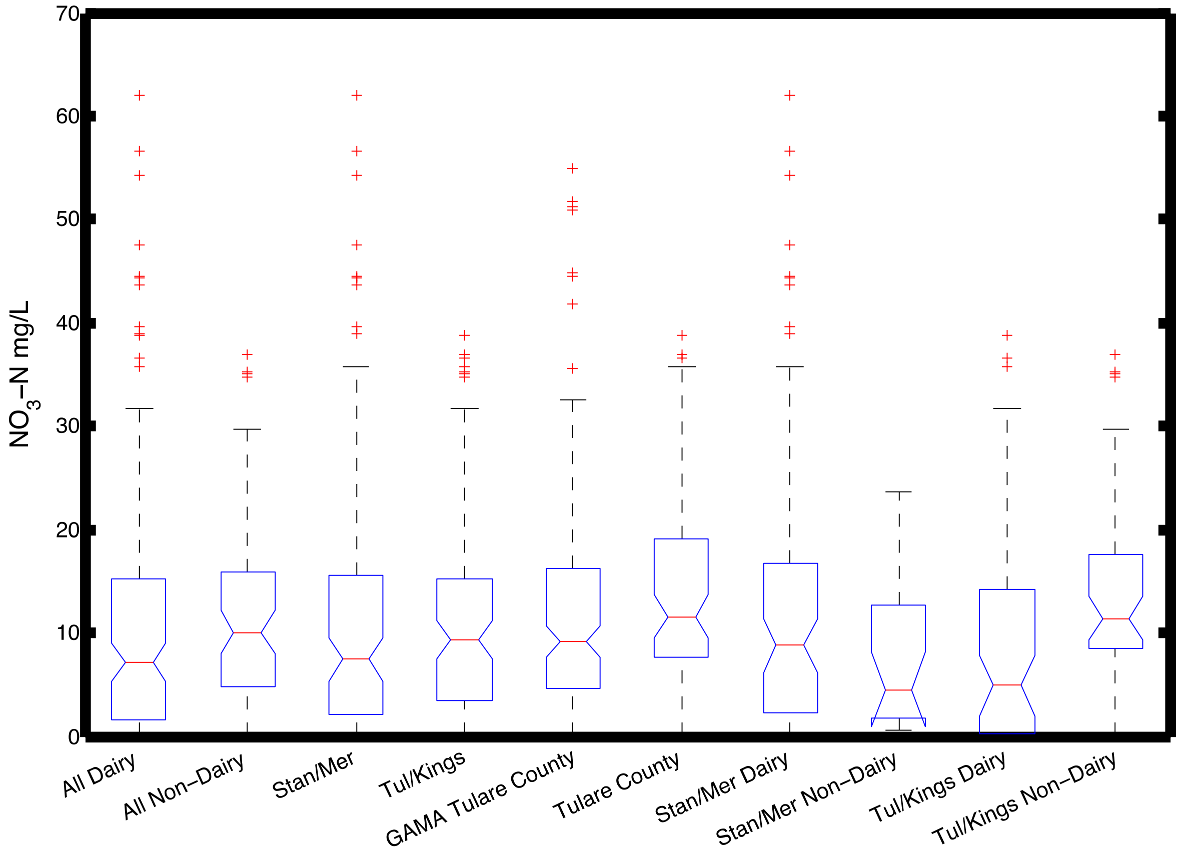


Figure 6: Boxplot of nitrate as nitrogen in well water samples for various groups: the central mark is the median, the lower and upper edges of the box are the 25th and 75th percentiles, respectively, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as red plus signs. GAMA is the Groundwater Ambient Monitoring and Assessment Program conducted by the California State Water Resources Control Board, 2006 Tulare domestic well study (California State Water Resources Control Board, 2010).

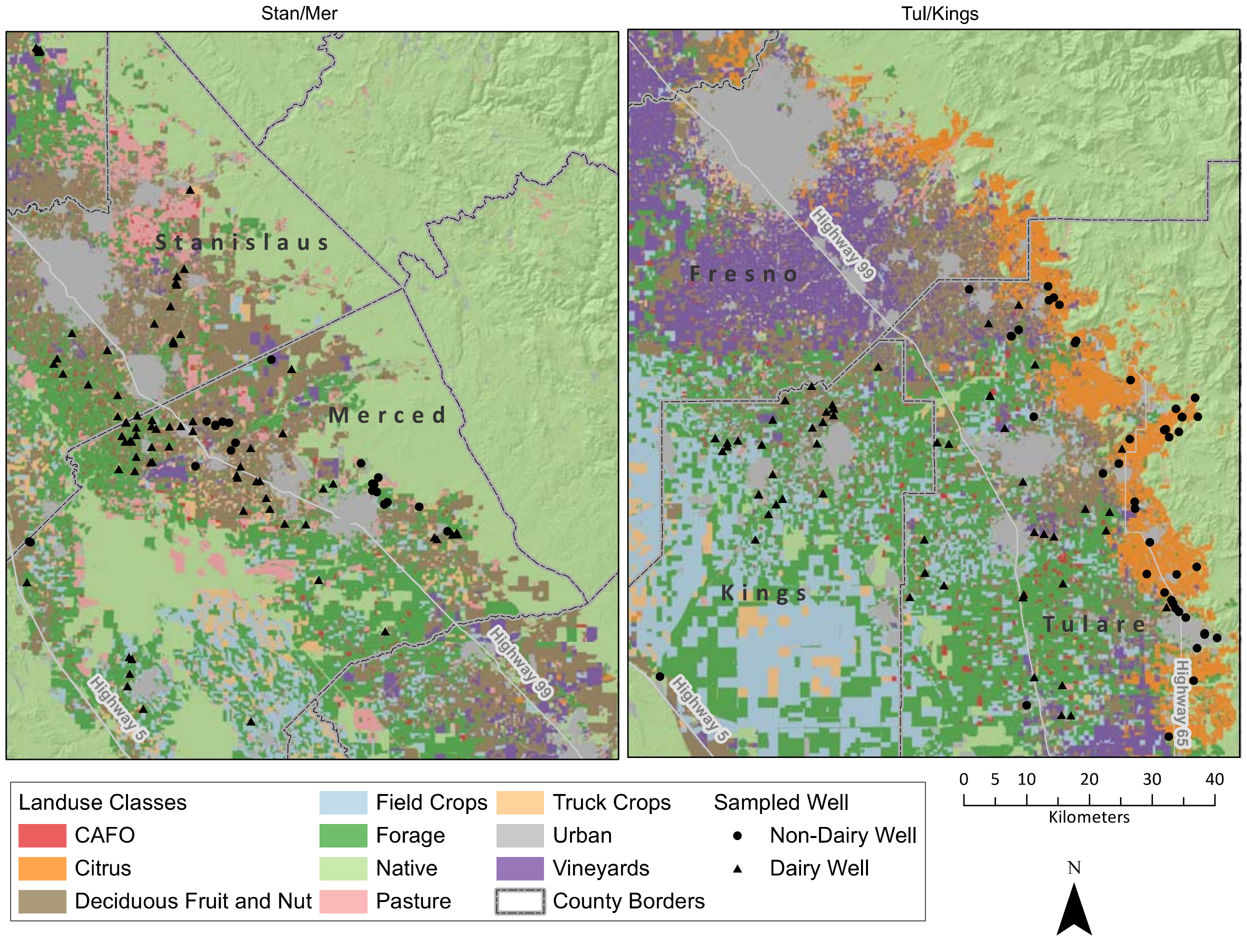


Figure 7: Landuse categories in Stan/Mer project area and Tul/Kings project area.

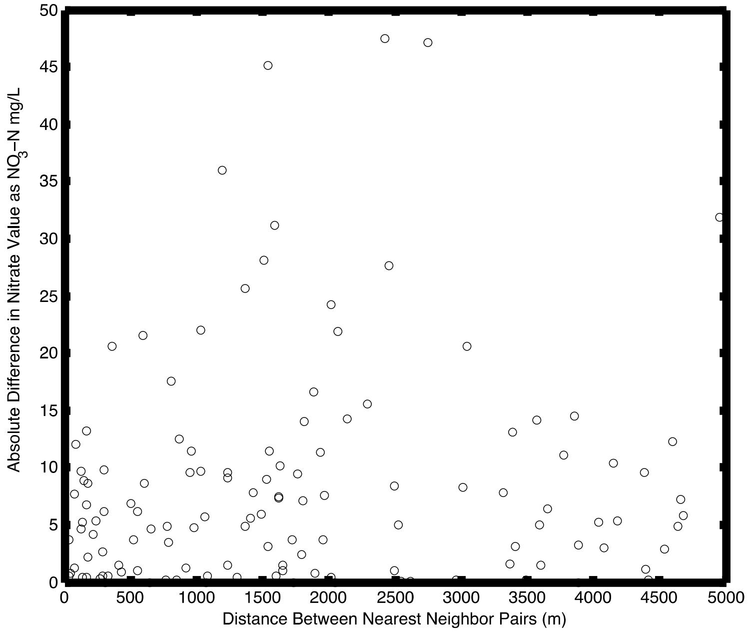


Figure 8: Scatterplot of distance between nearest neighbor well pairs and absolute difference in nitrate value for wells closer than 5 km (3 miles).

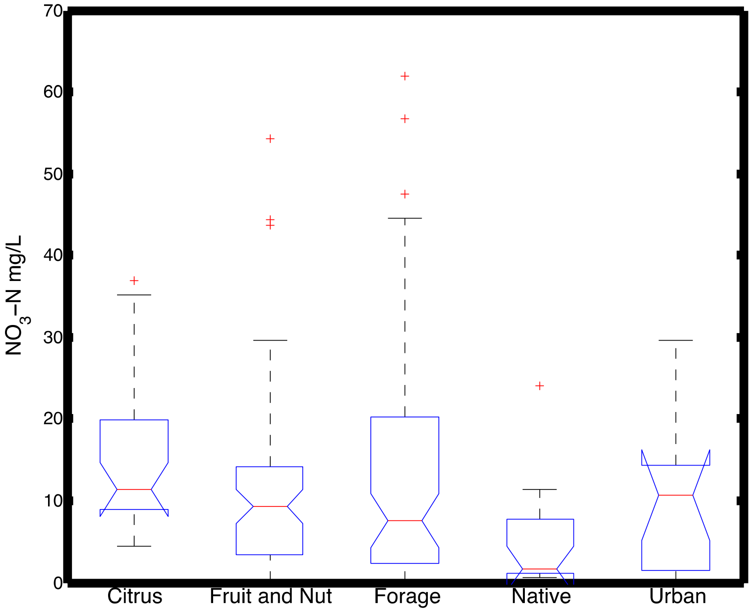


Figure 9: Boxplot of nitrate as nitrogen in well water samples for wells classified by dominant landuse

in well buffer. The central mark is the median, the lower and upper edges of the box are the 25th and 75th percentiles, respectively, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as red plus signs.

7. Acknowledgements

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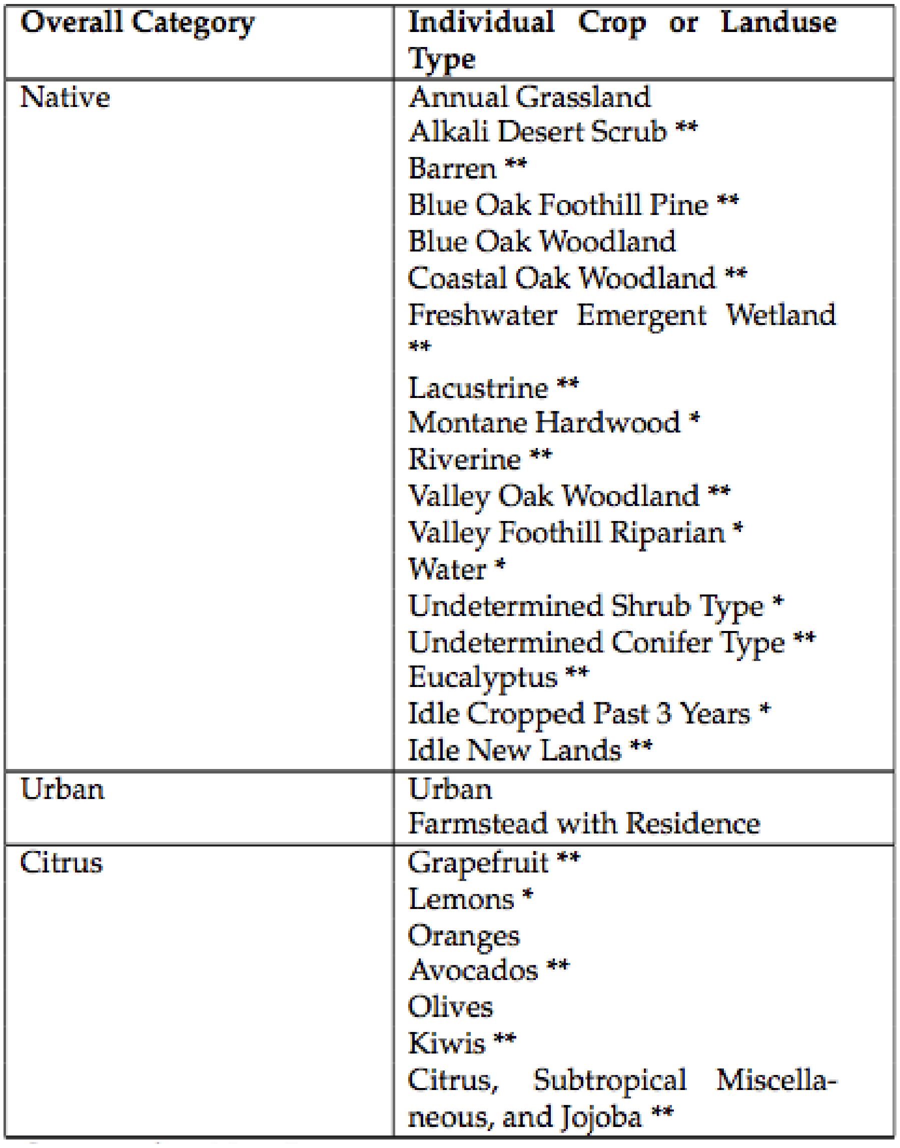
Appendix A: Landuse Groupings

Table A1: Individual crops or landuse types included in overall categories.



Overall Category	Individual Crop or Landuse Type
Native	Annual Grassland Alkali Desert Scrub ** Barren ** Blue Oak Foothill Pine ** Blue Oak Woodland Coastal Oak Woodland ** Freshwater Emergent Wetland ** Lacustrine ** Montane Hardwood * Riverine ** Valley Oak Woodland ** Valley Foothill Riparian * Water * Undetermined Shrub Type * Undetermined Conifer Type ** Eucalyptus ** Idle Cropped Past 3 Years * Idle New Lands **
Urban	Urban Farmstead with Residence
Citrus	Grapefruit ** Lemons * Oranges Avocados ** Olives Kiwis ** Citrus, Subtropical Miscellaneous, and Jojoba **

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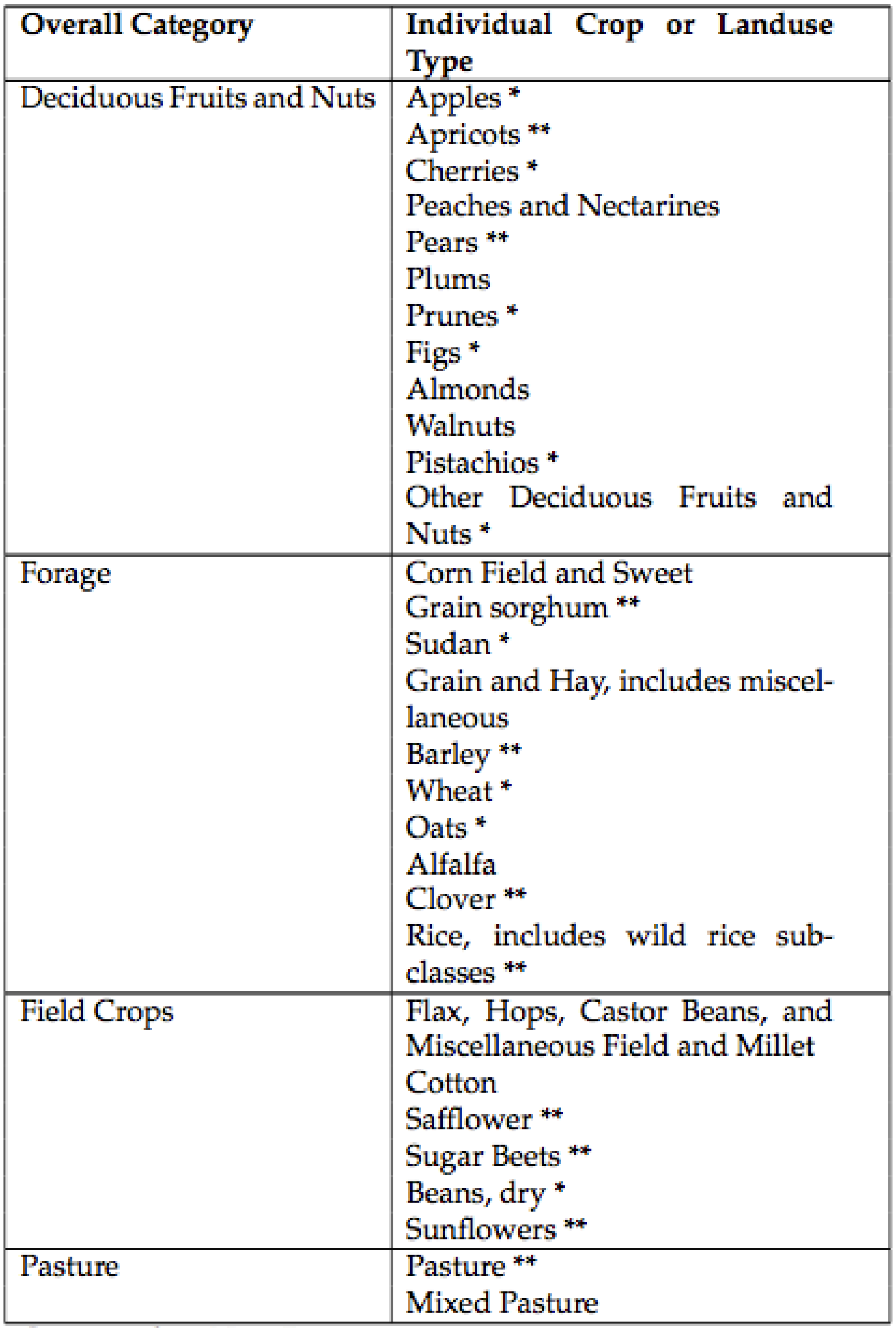

Overall Category	Individual Crop or Landuse Type
Deciduous Fruits and Nuts	Apples * Apricots ** Cherries * Peaches and Nectarines Pears ** Plums Prunes * Figs * Almonds Walnuts Pistachios * Other Deciduous Fruits and Nuts *
Forage	Corn Field and Sweet Grain sorghum ** Sudan * Grain and Hay, includes miscellaneous Barley ** Wheat * Oats * Alfalfa Clover ** Rice, includes wild rice subclasses **
Field Crops	Flax, Hops, Castor Beans, and Miscellaneous Field and Millet Cotton Safflower ** Sugar Beets ** Beans, dry * Sunflowers **
Pasture	Pasture ** Mixed Pasture

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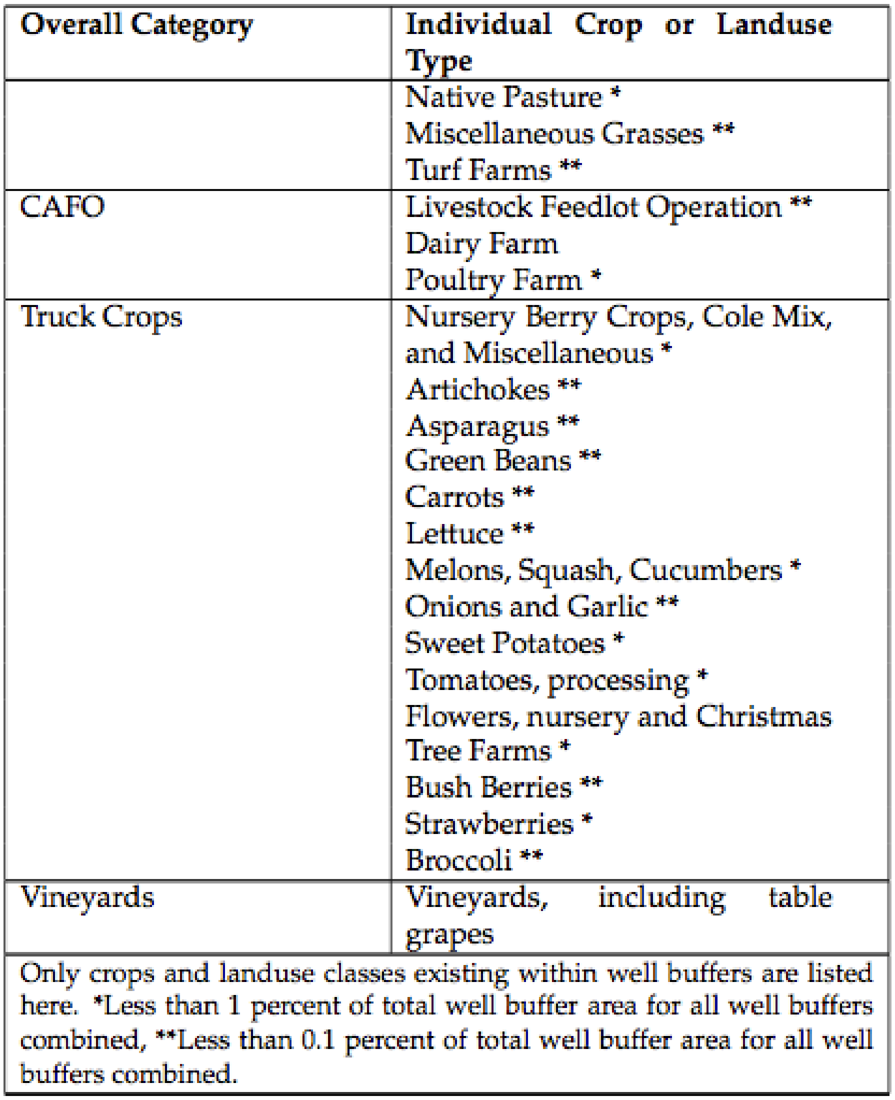

Overall Category	Individual Crop or Landuse Type
	Native Pasture * Miscellaneous Grasses ** Turf Farms **
CAFO	Livestock Feedlot Operation ** Dairy Farm Poultry Farm *
Truck Crops	Nursery Berry Crops, Cole Mix, and Miscellaneous * Artichokes ** Asparagus ** Green Beans ** Carrots ** Lettuce ** Melons, Squash, Cucumbers * Onions and Garlic ** Sweet Potatoes * Tomatoes, processing * Flowers, nursery and Christmas Tree Farms * Bush Berries ** Strawberries * Broccoli **
Vineyards	Vineyards, including table grapes

Only crops and landuse classes existing within well buffers are listed here. *Less than 1 percent of total well buffer area for all well buffers combined, **Less than 0.1 percent of total well buffer area for all well buffers combined.

Appendix B: Justification for Choice of 2.4 km Well Buffers

Under ideal aquifer conditions with homogeneous hydraulic conductivity and uniform regional groundwater gradients, the source area of domestic wells in alluvial aquifers are long and narrow with pumping in the domestic well affecting groundwater flow direction only within a few feet to tens of feet from the well. Domestic well pumping rates are small averaging usually less than 4 liters per minute (1 gpm, 3 acft/yr). The maximum extent of the source area, under ideal conditions, is determined by the depth of the well and the ratio of (uniform) recharge rate and (uniform) horizontal groundwater flow rate (Horn and Harter, 2009).

Groundwater recharge in the Central Valley comes mostly from excess irrigation water and varies with climatic changes (Faunt, 2009). Ground- water recharge rates for the Central Valley have been estimated at 0.18, 0.09, 0.37 m/year (0.6, 0.28, and 1.2 ft/year) for an average, dry, and wet water year, respectively (Faunt, 2009). For a more local perspective the average annual recharge rate for the Modesto area is 0.55 m/year (1.8 ft/year), but varies between 0.23 - 0.76 m/year (0.75 - 2.5 ft/year) through- out the area (based on water year 2000) (Burow et al., 2004). Due to the variable recharge rates on a regional, local, and temporal scale, 0.30 m/year (1 ft/year) was chosen for our calculations as a general approximation for recharge rates throughout the two project areas. At recharge rates on the order of 0.30 m/year (1 ft/year), given typical domestic pumping rates, the total source area of a domestic well in the Central Valley is therefore only on the order of one hectare (few acres) in size.

Since groundwater flow directions are highly variable in space and time due to local groundwater pumping by large production wells and due to groundwater heterogeneity, a circular source area (well buffer zone), extending to the maximum length of a typical domestic well source area, capture the overall area within which the actual source area is located. Any location within the circular well buffer zone is equally likely to con- tribute recharge to the domestic well, but at a relatively low probability (less than 1%). The low probability is obtained by taking the ratio of the estimated size of the source area (about 1 ha) and the size of the circular well buffer zone (> 100 ha, see below).

An approximate well depth was chosen based on the median completed well depth of 61 m (or approximately 200 ft) for sampled wells in Tul/Kings, which was slightly deeper than the median completed well depth of 54.9 m (or approximately 180 ft) for sampled wells in Stan/Mer. An approximate effective aquifer horizontal hydraulic conductivity (K) of 30.5 m/day (100 ft/day) was chosen based on the Tule Subbasin Ground- water Model produced by Ruud et al. in 2003 (Ruud et al., 2003), where Ruud et al. calculated horizontal hydraulic conductivities for the aquifer to be anywhere from 0.15 to 107 m/day (0.5 to 350 ft/day).

In the Modesto area, Burow et al. found a hydraulic gradient (I) of approximately 0.002 for the shallower part of the aquifer (less than 85.3 m or 280 ft) and a gradient of approximately 0.001 for the deeper part of the aquifer (around 85.3 m or 280 ft) (Burow et al., 2008). Actual hydraulic gradients at each domestic well can vary widely depending on local groundwater pumping and site conditions: exact gradients are impossible to determine without the installation of monitoring wells and long term monitoring. Therefore, 0.001 was chosen as an approximate groundwater gradient.

To calculate groundwater lateral movement, use Darcy’s Law to find specific discharge (Equation A.1):

$q = KI$ (B.1) $K = 30.5\text{m/day}$

$I = 0.001$⍰$q = (30.5\text{m/day})(0.001)(356\text{day/year}) = 13.0\text{m/year}$

Using the 0.30 m/year value for recharge and assuming mass is conserved within the system, you have 0.30 m of downward movement for every 13.0 m of lateral movement.

Therefore, for a 61 m deep well the radius of influence is:

$(61\text{m}/0.30\text{m})(13.0\text{m})(1\text{km}/1000\text{m}) \approx 2.4\text{km}(1.5\text{mile})$ This gives a total well buffer area of 1831 hectare (4524 acres).