San Joaquin County and Delta Water Quality Coalition Groundwater Quality Assessment Report, April 27, 2015

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Executive Summary

The San Joaquin County and Delta Water Quality Coalition Service Area encompasses 618,000 acres of irrigated cropland and approximately 6,000 growers. A Regional Board Order proposes to implement the long-term Irrigated Lands Regulatory Program within the Coalition Service Area. The primary groundwater quality concern is nitrate.

The Order tasks the Coalition with developing a Groundwater Quality Assessment Report (GAR) within the first year after adoption of the Order to analyze existing data and provide the foundation for designing the Management Practices Evaluation Program and the Groundwater Quality Trend Monitoring Program, as well as identifying high vulnerability groundwater areas where a groundwater quality management plan must be developed and implemented. The GAR shall include the following:

- Assessment of all available, applicable and relevant data and information to determine the high and low vulnerability areas where discharges from irrigated lands may result in groundwater quality degradation,
- Establish priorities for implementation of monitoring and studies within high vulnerability areas;
- Provide a basis for establishing workplans to assess groundwater quality trends;
- Provide a basis for establishing workplans and priorities to evaluate the effectiveness of agricultural management practices to protect groundwater quality; and
- Provide a basis for establishing groundwater quality management plans in high vulnerability areas and priorities for implementation of those plans.

Within the Coalition Service Area, the WDRs stipulate that the GAR may be divided into two phases; (1) non-Delta groundwater conditions and (2) Sacramento-San Joaquin Delta groundwater conditions. The Coalition has elected to include both phases in this one GAR.

To satisfy the objectives of the GAR, we gathered and analyzed available physical and chemical data for groundwater throughout the Coalition Service Area to help define factors influencing groundwater quality and define high and low vulnerability areas. The analysis included geochemical and statistical analysis, mapping of groundwater quality and relevant attributes, assessment of concentration trends, analysis of Delta subsurface conditions, hydrologic and geochemical analysis of Delta groundwater-surface water interactions and delineation of vulnerability areas and options for groundwater monitoring

Within the non-Delta portion of the Coalition Service Area, there are three California Department of Water Resources groundwater subbasins of the San Joaquin Valley Groundwater Basin: Cosumnes, Eastern San Joaquin and Tracy subbasins. Texturally, these formations and deposits consist of clay, silt, sand and gravel. In the alluvial fan areas, coarse-grained deposition (sand and gravel) predominate. Primary sources of groundwater recharge are percolation of precipitation, agricultural irrigation and urban return flows, reservoirs, and seepage from rivers. Surface water draining from the Sierra Nevada stored in reservoirs and diverted for irrigation and water supply, is the largest source of groundwater recharge. Groundwater discharges via pumping withdrawals for irrigation and municipal water supply, flows to streams, and evaporation and transpiration by plants in areas with shallow groundwater. Groundwater levels have mostly declined during the last 2 to 5 decades except where surface water supplies exist.

Key Findings

Non-Delta Area

In the non-Delta area, our assessment indicated that the number of wells with relatively high nitrate concentrations generally increased with time. However, the number of wells sampled also increased with time. From 2009 – 2013, wells in agricultural areas with average nitrate concentrations at or above the MCL were located primarily in the northern and southwestern parts of the Coalition Service Area, southern Delta and southwest of the Delta.

Well depths within agricultural areas ranged from 44 to 775 feet below land surface. For all nitrate data, concentrations above the MCL were associated with wells shallower than 250 feet. Depth to groundwater generally ranges from 200 feet in the northeastern part of the Coalition Service Area to less than 20 feet near the Delta. Nitrate concentrations over one-half the MCL are predominantly associated with areas where groundwater levels are within 100 feet of land surface. Nitrate concentrations were positively and significantly correlated with salinity and salinity-related variables. Since groundwater salinity generally increases with increasing proximity to the San Joaquin River where groundwater levels are shallowest, the higher nitrate concentrations are likely the result of the shallow water levels which are spatially associated with the higher salinities.

We conducted multiple linear regressions of maximum nitrate concentrations (dependent variable) with recharge, depth to water, fertilizer application rate, subsurface texture, and soil texture (independent variables). All regression models explained a relatively small percentage of the nitrate variance (maximum R^2 was 6.2%) and missed the mark in encompassing groundwater nitrate concentrations over the MCL in several key areas. The inability of the regression analysis to effectively predict all areas of high nitrate concentrations, to explain a substantial portion of the variance in nitrate concentrations, or indicate significant explanatory factors or processes, led us to conclude that mapping the spatial variability for delineation of vulnerability areas could be more effectively accomplished using geostatistics, i.e. indicator kriging and the DRASTIC methodology. Indicator kriging provided a map showing probabilities of exceedances for specified concentrations. We adjusted indicator kriging results using groundwater flow model results to delineate areas where groundwater from upgradient agricultural areas may influence groundwater supplies in downgradient communities where groundwater is used. We also adjusted the indicator kriging results to encompass where nitrate concentrations were mapped as over the maximum contaminant level of 45 mg/L. All wells with increasing nitrate concentrations are located within this area.

In addition to kriging, we used the EPA DRASTIC methodology to delineate areas where groundwater is intrinsically vulnerable to nitrate and other contaminants moving from land surface in alluvial systems. The DRASTIC methodology accounts for depth to groundwater, groundwater recharge, aquifer and soil texture, topography, influence of the vadose zone and aquifer hydraulic conductivity. A DRASTIC score was assigned for each pixel in our GIS system. DRASTIC scores were classified as very low, low, medium and high based on comparisons with scores in other alluvial systems and available groundwater quality data. The combination of DRASTIC scores, indicator kriging results and groundwater particle tracking results were used to delineate a high vulnerability area of 392,400 acres. The high vulnerability area was divided into three subareas for prioritization for conducting monitoring programs and carrying out required studies. The two agricultural land use classes having the largest area within the high vulnerability area are grain and hay crops (78,200 acres) and deciduous fruits and nuts (77,000 acres). Over 88% of the agricultural land in the high vulnerability areas are composed of five land use classes; grain and hay crops (27.6%), deciduous fruits and nuts (27.2%), vineyards (15.9%), pasture (11.1%), and truck, nursery, and berry crops (6.4%).

Delta Area

The primary objective of data analysis in the Delta was to assess groundwater- surface water interactions, need for groundwater monitoring and groundwater quality. The published conceptual model for groundwater-surface-water relations states that groundwater on subsided Delta islands is derived from adjacent channels and is collected by networks of drainage ditches. We reviewed and analyzed the readily available data and literature to provide a description of the surface-groundwater interactions for Delta islands within the Coalition Service Area to assess the extent of the applicability of conceptual model within the Coalition Service Area.

Data included land-surface elevations, subsurface lithology, organic deposit bottom elevations groundwater levels, channel stage and isotope data for groundwater and surface water samples. We initially delineated the area where artesian conditions exist. An artesian condition is defined by groundwater levels in wells screened in the aquifer underlying the organic deposits that rise above the bottom of the organic deposits. Artesian conditions are a clear demonstration of the influence of adjacent channels on island groundwater levels and upward flowing groundwater.

Outside the area delineated as artesian, where groundwater elevations are below sea level, there is also upward flowing groundwater. We performed calculations that demonstrate that where land-surface elevations are about 5 feet above sea level or less, groundwater flows upward towards drainage ditches from tens of feet below land surface. This area includes about 240,000 acres or 55 % of the Legal Delta within the Coalition Service Area where groundwater generally does not flow downward to wells. In this area, monitoring of shallow groundwater can be accomplished using drain-water samples. For the remaining area of the Delta within the Coalition Service Area, the data indicated a lack of water quality issues related to irrigated agriculture in water-supply wells. Hence, high vulnerability areas which encompass an area 392,400 acres (20% of the total Coalition Service Area) were delineated where nitrate concentrations were over the MCL and groundwater contributed to urban areas served by groundwater south and east of the Delta. We delineated the Delta as low vulnerability.

San Joaquin County and Delta Water Quality Coalition
Groundwater Quality Assessment Report, Draft, February 4, 2015

Introduction

The San Joaquin County and Delta Water Quality Coalition Service Area (Figure 1) includes groundwater subbasins and watersheds within San Joaquin County and parts of the Contra Costa, Amador, Calaveras, Alpine, Alameda, and Stanislaus counties. The Coalition Service Area encompasses 618,000 acres of cropland under irrigation by approximately 6,000 growers. About 36,000 acres are regulated under the Water Board's General Order for Existing Milk Cow Dairies (R5-2007-0035) and 459,000 acres are regulated under the San Joaquin County and Delta Water Quality Coalition Group Conditional Waiver.

A Regional Board Order proposes to implement the long-term Irrigated Lands Regulatory Program within the Coalition Area. The primary water quality concern is nitrate. Assessment of groundwater quality is necessary to evaluate member compliance with the terms and conditions of this Order and to assure protection of waters of the state.

Groundwater Quality Assessment Report

The Order tasks the Coalition with developing a Groundwater Quality Assessment Report (GAR) within the first year after adoption of the Order. The general purpose of the Groundwater Quality Assessment Report is to analyze existing data and provide the foundation for designing the Management Practices Evaluation Program and the Groundwater Quality Trend Monitoring Program, as well as identifying high vulnerability groundwater areas where a groundwater quality management plan must be developed and implemented. The GAR shall include the following:

- Assessment of all available, applicable and relevant data and information to determine the high and low vulnerability areas where discharges from irrigated lands may result in groundwater quality degradation;
- Establish priorities for implementation of monitoring and studies within High Vulnerability Areas (HVA);
- Provide a basis for establishing workplans to assess groundwater quality trends;
- Provide a basis for establishing workplans and priorities to evaluate the effectiveness of agricultural management practices to protect groundwater quality; and
- Provide a basis for establishing groundwater quality management plans in HVAs and priorities for implementation of those plans.

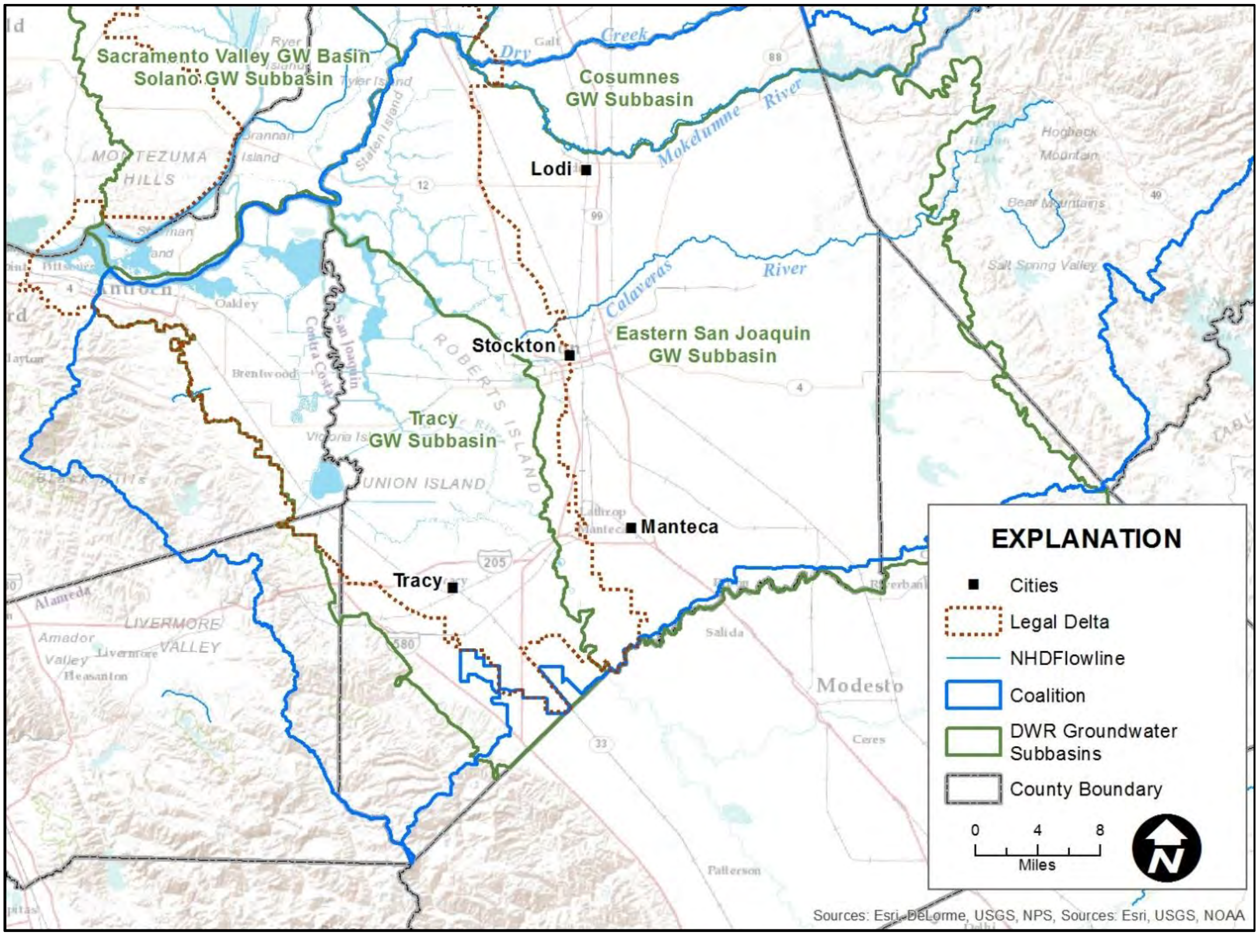

Figure 1. Location of San Joaquin County Delta Water Quality Coalition Service Area.

Phasing of the Groundwater Quality Assessment Report

Within the Coalition Service Area, the WDRs stipulate that the GAR may be divided into two phases:

1. Non-Delta groundwater conditions. The first phase will address groundwater conditions in the region, exclusive of the Delta.
2. Delta groundwater conditions. The second phase will address groundwater conditions in the Sacramento-San Joaquin Delta.

The Coalition has elected to include both phases in this one GAR.

Report overview

We gathered and incorporated available physical and chemical data for groundwater throughout the Coalition Service Area into a Microsoft Access database. We used Geographic Information System (GIS) software (ArcGIS) to interface with the database, develop maps, and perform calculations and analysis.

We summarized relevant hydrogeologic information and existing water quality data, methods and data sources, results of data gathering and analysis, and discussed and summarized key findings. To help define factors influencing groundwater nitrate concentrations, we utilized analysis of major-ion data, groundwater modeling and statistical and geostatistical analysis. In the Delta, analysis of subsurface conditions, hydrologic and geochemical data contributed to definition of Delta groundwater/surface water interactions, groundwater quality vulnerability and sampling needs. We also assessed concentration trends, delineated vulnerability areas relative to hydrogeologic and geographic features and listed options for groundwater monitoring

Hydrologic context

Non-Delta Area

The Coalition Service Area includes portions of the Sierra Nevada and Great Valley geomorphic provinces and is underlain by several thousand feet of sedimentary deposits[1]. Within the Coalition Service Area, there are three California Department of Water Resources (CDWR) groundwater subbasins of the San Joaquin Valley Groundwater Basin: Cosumnes, Eastern San Joaquin and Tracy subbasins (Figure 1). The Cosumnes Subbasin is bounded on the north and west by the Cosumnes River, on the south by the Mokelumne River, and on the east by consolidated bedrock of the Sierra Nevada Mountains. The largest groundwater subbasin within the Coalition Service Area, the Eastern San Joaquin Subbasin, encompasses unconsolidated and semi-consolidated sedimentary deposits that are bounded by the Mokelumne River on the north and northwest; San Joaquin River on the west; Stanislaus River on the south; and consolidated bedrock on the east. The Eastern San Joaquin Subbasin is drained by the San Joaquin, Stanislaus, Calaveras, and Mokelumne rivers. The Tracy Subbasin is bounded by the Diablo Range on the west; the Mokelumne and San Joaquin rivers on the north; the San Joaquin River to the east; and the San Joaquin-Stanislaus County line on the south.

Alluvium and Modesto/Riverbank, Laguna and Mehrten and Flood Basin Deposits are the primary water bearing formations within the Eastern San Joaquin Subbasin (Figure 1). The Mehrten Formation is

[1] California Department of Water Resources, 1967, San Joaquin County Investigation: Bulletin No. 146. California Department of Water Resources, Sacramento, Calif.

generally considered the oldest fresh water-bearing formation on the east side of the basin, even though the underlying Valley Springs Formation produces minor quantities of water[2]. Texturally, these formations and deposits consist of clay, silt, sand and gravel. In the alluvial fan areas, coarse-grained deposition (sand and gravel) predominate. Presence of fine grained (clay and silt) layers results in varying degrees of groundwater confinement[3].

Hydraulic Conductivity

For the development of the Central Valley Hydrologic Model, Faunt[4] estimated horizontal and vertical hydraulic conductivities based on the distribution of sediment texture. Other groundwater flow models in the San Joaquin Valley have used similar methods in which each cell has an estimated sediment texture (coarse-grained percentage) based on well completion reports and vertical and horizontal conductivity estimates for each textural end member (0 and 100% coarse-grained)[5]. End-members vary by layer and were estimated primarily based on data described in Phillips and Belitz[6]. We extracted the hydraulic conductivity values from model output for the Central Valley Hydrologic Model within the Coalition Service Area. Horizontal conductivity values range from 0.03 to 525 feet per day for the 10 model layers which include depths to 1,800 feet below land surface (Table 1). Vertical hydraulic conductivities range from 0.0003 to 3,281 feet per day.

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[2] California Department of Water Resources, California's Groundwater Bulletin, San Joaquin Valley Groundwater Basin, Eastern San Joaquin Subbasin. Groundwater Basin Number: 5-22.01

[3] Confined groundwater is contained within an aquifer that is bounded above and below layers of low permeability. Discontinuous layers of confining clays can result is spatially variable and localized confinement.

[4] Faunt, C.C., ed., 2009, Groundwater Availability of the Central Valley Aquifer, California: U.S. Geological Survey Professional Paper 1766, 225 p.

[5] e.g Phillips, S.P., and Belitz, Kenneth, 1991, Calibration of a textured-based model of a ground-water flow system, western San Joaquin Valley, California: Ground Water, v. 29, no. 5, p. 702–715.

Brush, C.F. Belitz, Kenneth, Phillips, S.P., Burow, K.R., and Knifong, D.L., 2006, MODGRASS: Update of a ground-water flow model for the Central Part of the Western San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2005-5290, 81 p.

[6] Ibid

Table 1. Ranges of hydraulic conductivity (K) values used in the Central Valley Hydrologic Model. In layers 4 & 5, depth is variable since it was set up to explicitly represent the Corcoran Clay layer where it exists; elsewhere a 1 foot thick phantom layer; they are kept only to keep track of layer numbers. The Corcoran layer thickness can range from 1 – 200 feet where it exists.

Layer	Depth to bottom of layer (ft)[4]	Horizontal K (feet/day)			Vertical K (feet/day)		
		Minimum	Maximum	Geometric Mean	Minimum	Maximum	Geometric Mean
1	50	39	525	194	0.02	0.34	0.11
2	150	0.03	474	0.32	0.25	3281	285
3	300	0.26	505	185	0.0003	0.33	0.11
4	Variable	0.03	4.3	0.04	0.0003	3281	934
5	Variable	0.03	4.3	0.04	0.0003	3281	934
6	500	15	32	122	0.0236	0.14	0.07
7	750	0.26	327	73	0.0003	0.06	0.04
8	1,050	0.26	274	60	0.0003	0.04	0.03
9	1,400	0.26	201	31	0.0003	0.03	0.02
10	1,800	0.26	205	12	0.0003	0.03	0.01

Groundwater inflows and outflows

Primary sources of groundwater recharge (water that reaches and replenishes the groundwater) are percolation of precipitation, agricultural irrigation and urban return flows, reservoirs, and seepage from rivers[7]. Surface water draining from the Sierra Nevada, stored in reservoirs and diverted for irrigation and water supply, is the largest source of groundwater recharge[8]. Groundwater discharges via pumping withdrawals for irrigation and municipal water supply, flows to streams, evaporation, and transpiration by plants in areas with shallow groundwater.

Faunt[9] described inflows and outflows to the Valley groundwater system for incorporation in their groundwater flow model. Faunt assumed no groundwater flow from boundaries at Sierran-alluvial interface at the eastern edge of the Coalition Service Area. Faunt also quantified surface-water inflow to the Valley from the Sierra Nevada ranging from 500 to 1,000 thousand acre-feet/year from the Mokelumne River.

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[7] Burow, K.R., Shelton, J.L., Hevesi, J.A., and Weissmann, G.S., 2004, Hydrogeologic characterization of the Modesto area, San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2004-5232, 54 p. (Also available at: http://pubs.usgs.gov/sir/2004/5232/.)
Phillips, S.P., Green, C.T., Burow, K.R., Shelton, J.L., and Rewis, D.L., 2007, Simulation of multi-scale ground-water flow in part of the northeastern San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2007-5009, 43 p. (Also available at: http://pubs.usgs.gov/sir/2007/5009/.)

[8] Phillips, S.P., Green, C.T., Burow, K.R., Shelton, J.L., and Rewis, D.L., 2007, Simulation of multi-scale ground-water flow in part of the northeastern San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2007-5009, 43 p. (Also available at: http://pubs.usgs.gov/sir/2007/5009/.)

[9] See footnote 4.

Groundwater level trends

In the Non-Delta areas we reviewed and analyzed data from San Joaquin County, CDWR, United States Geological Survey (USGS) and San Joaquin County Flood Control and Water Conservation District. Data reported by the San Joaquin County Flood Control and Water Conservation District[10] shows that groundwater levels have mostly declined during the last 2 to 5 decades due to groundwater withdrawal. Wells where declines were not observed are near the southern Delta and within the Central San Joaquin Water Conservation District and Stockton East Water District where there are surface water supplies.[11]

Groundwater Quality

The primary groundwater quality issues were determined from reviewed data and literature. The primary constituent of concern related to agriculture is nitrate. Bennett and others[12] reported high nitrate concentrations relative to the MCL in 2.1% of the primary aquifer within the three groundwater subbasins in the Coalition Service Area. They also reported high nitrate concentrations associated with oxygenated groundwater conditions. Anoxic conditions generally result in chemical reduction of nitrate to nitrogen gas and removal of nitrate from groundwater. Higher concentrations were also reportedly associated with orchards and vineyards. However, Bennett and others expressed uncertainty as to whether this was an artifact of well selection or land-management practices.

Other constituents of concern related to agriculture considered here include salinity and pesticides. Increasing salinity is a consequence of decreasing groundwater levels in some areas of the Coalition Service Area. Salinity originates from the marine deposits that contain saline water in most parts of the Coalition Service Area. The extent of higher salinity groundwater has increased eastward due to groundwater withdrawal and associated declining water levels since the 1980s.[13, 14] For organic constituents, the USGS[15] determined that relative to appropriate benchmark concentrations, concentrations of these constituents were high in 2.7%, moderate in 6.9%, and low in 90% of the primary aquifer within the Coalition Service Area. They reported that the discontinued soil fumigant 1,2-dibromo-3-chloropropane (DBCP) which was high relative to benchmark concentrations in 2.7 percent of the primary aquifer. Agricultural herbicides Simazine and Atrazine were detected at low concentrations relative to benchmark concentrations.

During the conduct of the Groundwater Ambient Monitoring and Assessment (GAMA) within the Coalition Service Area, the USGS identified boron and arsenic at high levels relative to their respective benchmark concentrations (Maximum Contaminant Level or MCL for drinking water for arsenic and the California Department of Public Health Notification Level for boron) in 9.4% and 7.6% of the wells

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[10] San Joaquin Flood Control and Water Conservation District, 2012, Groundwater Report, Spring 2012, San Joaquin County Department of Public Works.

[11] San Joaquin County, 2001, Water Management Plan, Phase 1 – Planning, Analysis and Strategy, Volume 2.

[12] Bennett, G.L., V, Fram, M.S., Belitz, Kenneth, and Jurgens, B.C., 2010, Status and understanding of groundwater quality in the northern San Joaquin Basin, 2005: California GAMA Priority Basin Project: U.S. Geological Survey Scientific Investigations Report 2010–5175, 82 p.

[13] California Department of Water Resources, California's Groundwater Bulletin, San Joaquin Valley Groundwater Basin, Eastern San Joaquin Subbasin. Groundwater Basin Number: 5-22.01.

[14] John A. Izbicki, Loren F. Metzger, Kelly R. McPherson, Rhett R. Everett, and George L. Bennett V, 2006, Sources of High-chloride water to wells, Eastern San Joaquin Ground-water Subbasin, California, USGS Open-File Report 2006-1309.

[15] See footnote 12.

evaluated[16], respectively. These constituents are naturally occurring in the soils and aquifer materials and elevated concentrations are not generally due to anthropogenic activities.

Boron generally behaves conservatively in natural waters but can be affected by pH –dependent adsorption onto soil minerals[17]. High boron concentrations, which are primarily a water-quality concern for agriculture, are generally associated with marine sediments near the San Joaquin River and high groundwater salinity. For shallow groundwater samples collected in San Joaquin Valley, Deverel and Millard[18] reported boron concentrations that were highly correlated with shallow ground water salinity. These authors reported that boron is present as a geochemically mobile oxyanion in the generally alkaline San Joaquin Valley soils and groundwater. Sources of boron include the Coast Range and Sierran sediments.[19] The primary water-quality concern for boron is plant sensitivity to concentrations over about 1 mg/L in irrigation water.[20]

The predominant factors governing arsenic levels in natural waters are the oxidation-reduction state of the water, aqueous-mineral interactions, and biochemical transformations[21]. At higher soil redox (200-500 mV), arsenic solubility is low when predominantly present as the pentavalent form. It is therefore generally immobile in oxidized soils. Under moderately chemically reducing conditions at oxidation-reduction potential values of 0-100 mV, arsenic solubility is controlled by the dissolution of iron oxides due to reduction of ferric to ferrous ion.

Izbicki and others[22] reported elevated arsenic concentrations in the Coalition Service Area are due to mobilization of arsenic from manganese and iron oxide minerals and aquifer sediments that contain adsorbed arsenic under chemically reducing conditions. Specifically, in the Coalition Service Area, Izbicki and others[23] reported groundwater arsenic concentrations were less than the MCL of 10 micrograms per liter (µg/L) where there were oxidizing conditions. Concentrations in groundwater samples increased with pH, consistent with exchange of arsenic adsorbed to iron and manganese hydroxides. In chemically reducing groundwater, arsenic concentrations ranged from 3 to 63 µg/L, with a median concentration of 10 µg/L[24]. Increases in arsenic concentrations under reducing conditions are consistent with reductive dissolution of iron and manganese hydroxides.

Delta Area

Land- and water-management practices substantially determined current groundwater-surface water relations on Delta islands (Figure 2). For over a century, subsidence of Delta organic soils or peats has

[16] See footnote 12.

[17] Deverel, Steven .J., Godlberg, Sabine, Fujii, Roger, 2012, Chemistry of Trace Elements in Soils and Groundwater, In (Wallender, W.W. and Tanji, K.K), ed.) Agricultural Salinity Assessment and Management, ASCE Manual of Practice 71, Second Edition. These authors summarized geochemical processes affecting arsenic in soils and groundwater.

[18] Deverel, S.J., and Millard, S.P. 1988. Distribution and mobility of selenium and other trace elements in shallow ground water of the western San Joaquin Valley, Calif. Environ. Sci. Technol. 22:697–702.

[19] ibid

[20] W. P. Chen, A. C. Chang Page, A.L., 2012, Deficiencies and toxicities of trace elements, In (Wallender, W.W. and Tanji, K.K), ed.) Agricultural Salinity Assessment and Management, ASCE Manual of Practice 7, Second Edition.

[21] See footnote 17.

[22] Izbicki, J.A., Stamos, C.L., Metzger, L.F., Kulp, T.R., McPherson, K.R., Halford, K.J., and Bennett, G.L., 2008, Sources, distribution, and management of arsenic in water from wells, Eastern San Joaquin ground-water sub-basin, California: U.S. Geological Survey Open-File Report 2008-1272, 8 p. (Also available at: http://pubs.usgs.gov/of/2008/1272/.)

[23] ibid

[24] ibid

resulted in an increasing need for subsurface drainage on Delta islands. Aerobic oxidation of organic carbon, the primary cause of subsidence[25], began in the late 1800s as the nutrient-rich soils were cleared and dewatered for agriculture. Since then, island elevations have decreased to as much as 25 feet below sea level and are protected from flooding by over 1,000 miles of man-made levees. Networks of ditches collect and transport levee seepage and irrigation and precipitation deep percolation to pumps that discharge to adjacent channels. As the peat oxidizes and disappears, farmers generally deepen drainage ditches to maintain a sufficient unsaturated root zone from crop production.

Delta peat and mud deposits formed during the last 7,000 years under tidal wetland conditions[26]. Plant material decayed and accumulated under anaerobic conditions as sea level increased[27]. Peat thicknesses generally decrease from the west to east and towards the periphery of the Delta. Peat thickness ranges from less than 3 feet on the eastern, southern, and northern margins of the Delta to over 30 feet in the western Delta[28]. Drainage of soils for agriculture has increased microbial oxidation of organic carbon which results in land subsidence at rates of less than 0.5 to over 1 inch per year[29].

There is substantial quantitative evidence from Twitchell Island for the conceptual model for groundwater-surface water interactions[30]. Figure 3 illustrates the conceptual model of physical and chemical processes affecting drain flow, chemistry and constituent loads. Groundwater flows from the San Joaquin River onto the island via organic and underlying mineral deposits. San Joaquin River water is also the source of irrigation water (Figure 3).

During low drain-flow conditions during May-November (Figure 3), observed drain-water quality was primarily influenced by deep (6 to 25 feet below land surface) groundwater flow to drainage ditches from chemically reduced permanently saturated organic deposits. During higher flow conditions in December-April (Figure 3), groundwater flowing from variably saturated peats determined drain-water chemistry. Groundwater age dating and tritium analysis of groundwater and drain-water samples support the conceptual model and provide evidence that time frames for groundwater flow to drainage ditches are decadal.

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[25] Deverel, S.J. and S. Rojstaczer. 1996. Subsidence of agricultural lands in the Sacramento-San Joaquin Delta, California: Role of aqueous and gaseous carbon fluxes. Water Resources Research 32(8):2359–2367.

[26] Atwater, B.F. 1982. Geologic Maps of the Sacramento-San Joaquin Delta, U.S. Geological Survey, Miscellaneous Field Studies Map MF – 1401.

Atwater, B.F. 1980. Attempts to correlate late quaternary climatic records between San Francisco Bay, the Sacramento – San Joaquin Delta, and the Mokelumne, University of Delaware Ph.D. Dissertation.

Atwater, B.F., Hedel, C.W., and Helley, E.J. 1977. Late Quaternary depositional history, Holocene sea-level changes and vertical crustal movement, south San Francisco Bay, California, U.S. Geological Survey Professional Paper 1014.Deverel and Leighton, 2010

[27] Shlemon, R.J. and Begg, E.L. 1975. Late Quaternary Evolution of the Sacramento-San Joaquin Delta, California in Suggate, R.P and Cressel, M.M. (Eds) Quaternary Studies, Bulletin 13, The Royal Society of New Zealand, Wellington, New Zealand, pp. 259-266.

[28] Deverel, Steven J, & Leighton, David A. 2010. Historic, Recent, and Future Subsidence, Sacramento-San Joaquin Delta, California, USA. San Francisco Estuary and Watershed Science, 8(2): http://www.escholarship.org/uc/item/7xd4x0xw

[29] ibid

[30]Deverel, Steven J., David A. Leighton and Mark R. Finlay. 2007. Processes Affecting Agricultural Drain-water Quality and Organic Carbon Loads in California's Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science. Vol. 5, Issue 2 [May 2007]. Article 2. http://repositories.cdlib.org/jmie/sfews/vol5iss2/art2

Figure **2**. The legal Delta within the Coalition Service Area.

In a more quantitative vein, Deverel and others[31] used groundwater flow and solute transport models for Twitchell Island to answer the following question. How do the groundwater flow and drainage systems interact to influence island drainage volumes and drain-water chemistry and constituent loads? The models were based on substantial field data for hydraulic conductivity, groundwater and surface-water elevations, drain flow and groundwater and drain-water chemical, isotopic and age-dating data. Model results were in good agreement with measured groundwater levels, drain flows, and loads.

The model results demonstrated that groundwater flows from the adjacent channels to the island center and drainage ditches. Table 2 summarizes the groundwater budget[32]. Water flows onto the island via precipitation and irrigation recharge and seepage from adjacent channels and leaves the island via drain flow which is pumped off the island. Also, groundwater levels are influenced by varying precipitation and irrigation recharge and San Joaquin River levels. Drain flows vary concomitantly with groundwater levels.

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[31] Deverel S.J., Leighton D.A., Sola–Llonch N. 2007b. Appendix C: Evaluation of island drain flow, seepage, and organic carbon loads, Sacramento–San Joaquin Delta. Results from the Delta Learning Laboratory Project, Objectives 2 and 3. Prepared for California Department of Water Resources and CALFED Bay Delta Authority under CDWR Agreement 4600000659 CALFED Project 98–C01, January 26, 2007.

[32] ibid

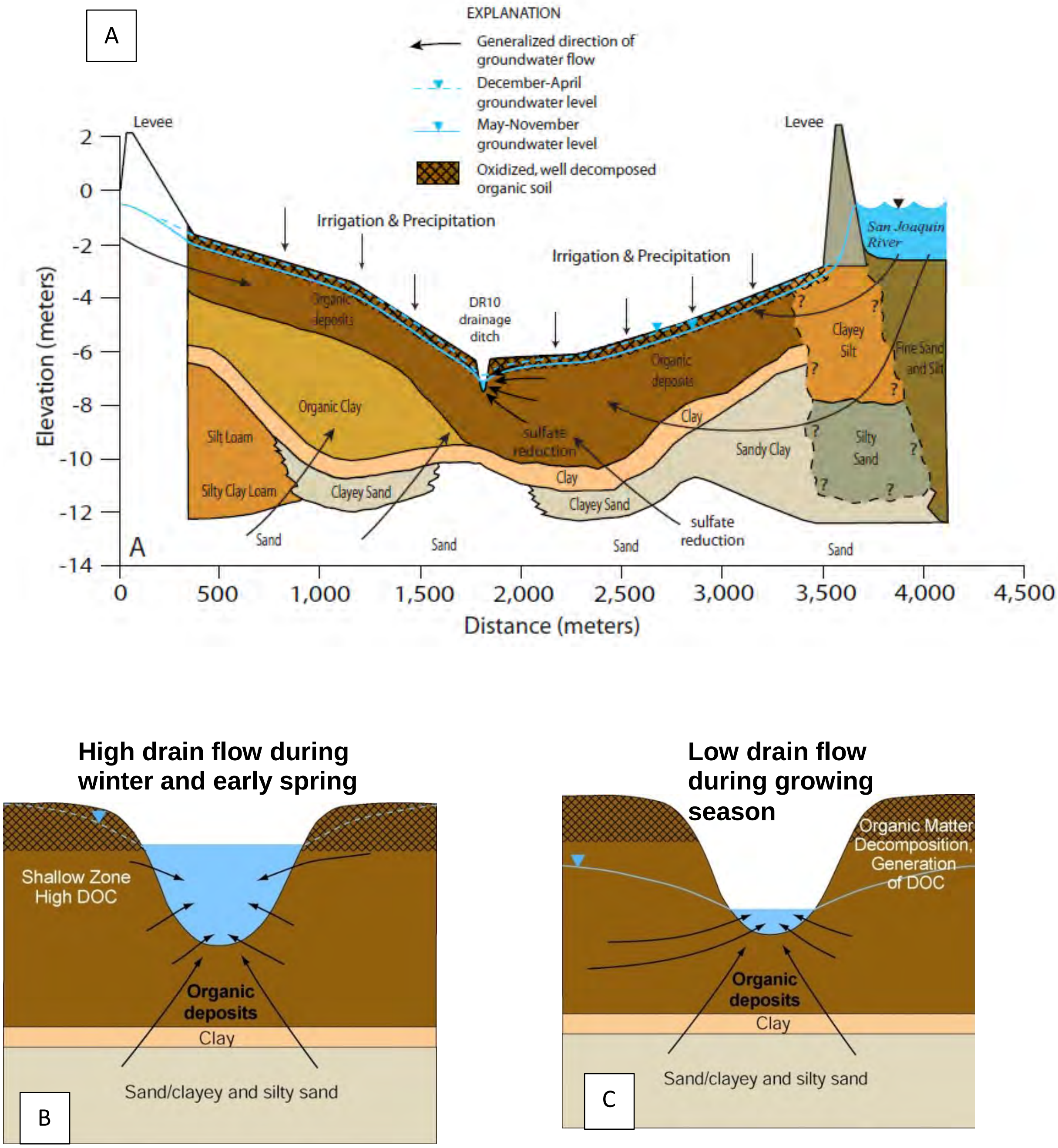

Figure 3. Conceptual model for groundwater-surface water interactions (modified from Deverel and others[33]). Water flows from the San Joaquin River towards the island center and drainage ditches (A). During winter and early spring, shallow zone water is the primary source of drain flow (B) during late spring to early fall, groundwater flow predominates drain flow (C).

[33] See footnote 30

Table 2. Calculated daily water budget for Twitchell Island groundwater-flow model[34].

Inflows	Volume in m³/d (acre-feet/d in parentheses)	Outflow	Volume (m³/d) (acre-feet/d in parentheses)
Seepage onto island from adjacent channels	11,100 (9.1)	Drain flow	30,000 (24.3)
Precipitation and irrigation recharge	18,900 (15.3)		
Total	**30,000 (24.4)**		

Hydraulic Conductivity

Hydraulic conductivity values vary substantially for shallow deposits which include tidal peat and mud deposits and underlying mineral materials. On Twitchell Island, HydroFocus[35] reported about 3 to 5 meters of tidal mud and organic deposits accumulated over the last 7,000 years overlaying material of Sierran origin[36] ranging in texture from sandy silt to medium and coarse sand. HydroFocus used single well response (slug) tests to estimate hydraulic conductivity and analyzed the results using methods described in Hvorslev[37] and Bouwer and Rice[38] and used tidal analysis[39, 40] to estimate the hydraulic conductivity of geologic materials near the levee. They also estimated groundwater hydraulic conductivity of the lower, confined mineral aquifer using groundwater age dating. Ranges of horizontal conductivities for the shallow organic deposits ranged from 0.328 – 118 ft/d. Horizontal hydraulic conductivity values ranged from 0.0492 ft/d to 5.28 ft/d in the mineral aquifer underlying the tidal organic and mud deposits. Using the tidal analysis method, HydroFocus estimated a range of hydraulic conductivity of the materials near the levee. For wells screened in less decomposed organic soil, values ranged from 0.052 ft/d to 0.102 ft/d. Values for mineral deposits adjacent to the levee ranged from 0.29 ft/d plus or minus 1.5 ft/d. Using undisturbed cores collected on Twitchell Island within 10 feet of land surface, the USGS [41] estimated horizontal hydraulic conductivity values for organic determined in the laboratory ranging from 0.0098 ft/d to 133.86 ft/d.

From aquifer test results at the Ironhouse Sanitary District monitoring wells on Jersey Island and the mainland, which were constructed in similar mineral sediments next to the canal in the reach west of Marsh Creek, hydraulic conductivity values ranged from 0.5 to 6 ft/d [42]. In general, subsurface conditions are characterized by about 5-feet of dense clay and silty-clay, underlain by sand, silty sand,

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[34] See footnote 28

[35] See footnote 31

[36] See footnote 30

[37] Hvorslev, M.J. 1951. Time Lag and Soil Permeability in Ground-Water Observations, bul. no. 26, Waterways Experiment Station, Corps of Engineers, U.S. Army, Vicksburg, Mississippi.

[38] Bouwer, H. and Rice, R.C. 1976. A slug test method for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, Water Resources Research, vol. 12, no. 3, pp. 423-428.

[39] Erskine, A.D. 1991. The Effect of Tidal Fluctuation on a Coastal Aquifer in the UK, Journal of Ground Water, vol. 29, no. 4.

[40] Carr, P.A. and Van Der Kamp, G.S. 1969. Determining aquifer characteristics by the tidal method, Water Resources Research, v. 5, pp. 1023-1031.

[41] Tim Mathany, USGS, Sacramento, CA,. written communication, 2003.

[42] HydroFocus. 2003. “Beneficial Use Impact Study, Ironhouse Sanitary District, Oakley, California.”

clayey sand and clayey silt deposits.[43] For seepage analysis, URS estimated hydraulic conductivity values for Webb Tract and Bacon Island for CDWR. Values for horizontal hydraulic conductivity ranged from 0.0028 ft/d to 0.28 ft/d for clay with peat and sand.

Groundwater level trends

Substantial groundwater-level data has been collected within the Delta. Deverel and others[44] reported groundwater levels for Twitchell Island. Delta Wetlands Project groundwater level data was collected from wells located on or near the levees throughout the Delta[45]. These and additional data generally show little change in groundwater levels in the Delta over time. These data are discussed in the Results section.

Key Delta groundwater quality issues

Shallow groundwater influences drain-water quality for much of the Sacramento-San Joaquin Delta within the Coalition Service Area where land-surface elevations are near or below sea level and where there are peat soils. The area of peat soils encompasses about 200,000 acres.[46] The key constituents of concern are dissolved organic carbon, methyl mercury, and salts which originate from the oxidation of drained peat soils. Deverel and others[47] described the processes resulting in mobilization and movement of salinity and dissolved organic carbon to drainage ditches. Heim and others[48] described processes and factors affecting mobilization and discharge of methyl mercury from Delta farmed islands.

Dissolved organic carbon can form harmful disinfection byproducts during disinfection of Delta water for drinking water. This organic carbon accumulates in the unsaturated zone during the growing season and is mobilized during the winter and spring and by irrigation and discharges into and through drainage ditches to Delta channels. Dissolved organic carbon and associated disinfection byproducts result from oxidation of organic soils and highly organic mineral soils drained for agriculture. Similarly, salts which are left behind when the peat oxidizes during the growing season are flushed to the drainage ditches during irrigation and winter rains.

Concern over mercury pollution in the Sacramento-San Joaquin Delta resulted in posting of fish advisories recommending limited human consumption. The mercury species of greatest concern to human health in the Delta is methyl mercury in fish. In aquatic systems, methyl mercury is readily bio-accumulated by phytoplankton and zooplankton and biomagnified up the food web, ultimately posing a threat to humans consuming fish. Methyl mercury results from the microbial conversion of mercury present in the soil and is mobilized to drainage ditches. To reduce mercury levels in Delta fish for human

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[43] ibid

[44] See footnote 30.

[45] Harding Lawson Associates. 1991. A Report Prepared for Delta Wetlands: Groundwater Data Transmittal No. 2 Delta Wetlands Monitoring Program Sacramento-San Joaquin River Delta.
Hultgren-Tillis Geotechnical Engineers. 1995. Groundwater Data Transmittal No. 4 Delta Wetlands Project Sacramento-San Joaquin River Delta.

[46] See Figure 2 in Deverel, Steven J, & Leighton, David A. 2010. Historic, Recent, and Future Subsidence, Sacramento-San Joaquin Delta, California, USA. San Francisco Estuary and Watershed Science, 8(2): http://www.escholarship.org/uc/item/7xd4x0xw

[47] See footnote 30.

[48] Heim W. A., Deverel S. J., Stephenson M. 2009. Farmed islands and monomethylmercury in the Sacramento–San Joaquin Delta. Final report submitted to the Central Valley Regional Water Quality Control Board.

consumption, the Regional Water Quality Control Board[49] has proposed water quality objectives for methyl mercury concentrations in Delta channels.

Few Delta methyl mercury shallow groundwater and drain-water concentration data are available. In a study assessing groundwater methyl mercury concentrations and drain loads on farmed Delta Islands, Heim and others[50] collected and analyzed methyl mercury samples both from wells and from agricultural return flow drains. On islands with mainly mineral soils, drain concentrations ranged from below the detection limit to 4.69 nanograms per liter (ng/L) with a median of 0.292 ng/L. On islands with mainly organic soils, drain concentrations ranged from 0.039 to 17.7 ng/L with a median of 0.329 ng/L. Samples from wells in cultivated fields had methyl mercury concentrations ranging from 0.196 to 8.54 ng/L, whereas from wells in wetlands they ranged from 0.030 to 0.064 ng/L. The authors found good evidence that concentrations were greater on islands with predominantly organic soils than on islands with predominantly mineral soils.

Chemical and physical data from Twitchell Island demonstrated two primary sources of subsurface flow to drainage ditches[51]. During December-April, substantial drain flow originates from within 1.5 m of land surface where oxidized and well decomposed organic soils predominate. The average DOC for this groundwater was 82.5 mg/L. During May-November, drain flow is predominantly from permanently saturated, moderately to undecomposed and anoxic organic deposits. The average DOC for this groundwater was 18.8 mg/L. Results for deeper well samples had a greater propensity to form disinfection byproducts per mole of DOC relative to shallow well samples. Dissolved organic concentrations in the underlying mineral aquifer were less than 10 mg/L.

Similar variations in groundwater were reported on Bouldin Island and Wright-Elmwood Tract[52]. Bachand and others[53] reported differences in DOC concentrations among shallow and deep well samples on the two islands. The medians for DOC for shallow-well samples (6 wells on Bouldin Island and 5 wells at Wright-Elmwood Tract) were 178 and 141 mg/L for the Bouldin Island and Wright-Elmwood Tract, respectively. The medians for DOC for deep-well samples (6 wells on Bouldin Island and 5 wells on Wright-Elmwood Tract) were 34 and 23 mg/L for the Bouldin Island and Wright-Elmwood Tract, respectively.

Available data indicate that nitrate is generally not prevalent in shallow groundwater in the Delta, especially in areas where there are organic soils. Nitrate concentrations from shallow groundwater samples collected by HydroFocus in the Dutch Slough area (2010-12) and Ironhouse Sanitary District ranged from below the detection limit to 159 mg/L. Removing data for wells located in a field irrigated

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[49] Wood M, Morris P, Cooke J, Louis S (2010). Amendments to the Water Quality Control Plan for the Sacramento River and San Joaquin River Basins for the Control of Methylmercury and Total Mercury in the Sacramento-San Joaquin Delta Estuary, Staff Report. Sacramento: Central Valley Regional Water Quality Control Board. Available online at http://www.swrcb.ca.gov/rwqcb5/water_issues/tmdl/central_valley_projects/delta_hg/april_2010_hg_tmdl_hearing/apr2010_bpa_staffrpt_final.pdf

[50] Heim, Wesley A., Steven Deverel, Timothy Ingrum, Witold Piekarski, and Mark Stephenson, "Assessment of Methylmercury Contributions from Sacrament-San Joaquin Delta Farmed Islands," submitted to Chris Foe and the Central Valley Regional Water Quality Control Board, August 2009.

[51] See footnote 30.

[52] Bachand & Associates, HydroFocus, Inc., US Geological Survey and UC Davis, Reducing Non-point DOC and Nitrogen Exports from Rice Fields: A Pilot Study and Quantitative Survey to Determine the Effects of Different Hydrologic Management Practices. March, 2006.

[53] ibid

with wastewater treatment-plant effluent, the maximum concentration was 12 mg/L.[54] Nitrate concentrations were below 0.1 mg/L in Bachand and Associates shallow (≤30 ft) groundwater samples from Twitchell Island (2012), and was only detected in two of 13 samples. Shallow (≤6 ft) groundwater samples collected by Bachand and Associates and HydroFocus personnel (2004-05) on Bouldin Island and Wright-Elmwood Tract yielded no nitrate detections above 0.1 mg/L.[55] Groundwater ammonia is more common. In the Bachand and Associates and HydroFocus study cited above, concentrations ranged from 0.01 to 1.7 mg/L. In the groundwater samples from Twitchell Island, ammonia concentrations ranged from 1.8 to 18 mg/L.

Groundwater Vulnerability Areas and Monitoring

Vulnerability

The California Department of Pesticide Regulation (DPR) initiated and administers the Ground Water Protection Program for monitoring and evaluating the potential for pesticides to move through soil to groundwater, improving contaminant transport modeling tools, and outreach/training programs for pesticide users. There are approximately 128,000 acres of irrigated lands in the San Joaquin County and Delta Water Quality Coalition Service Area within DPR Groundwater Protection Areas (GWPA). Groundwater Protection Areas were delineated using statistical clustering methods in which DPR attempted to identify similar geographic features among land areas where pesticides have been detected in groundwater[56]. Of the 128,000 acres of irrigated lands, approximately 92,000 acres are within DPR GWPAs that are characterized as vulnerable to leaching of pesticides (leaching areas), approximately 22,000 acres are within GWPAs that are characterized as vulnerable to movement of pesticides to groundwater by runoff from fields to areas were they may move to groundwater (runoff areas), and 14,000 acres are characterized as both leaching and runoff areas (Figure 4). The GWPA area within the Legal Delta within the Coalition Service Area is anomalous in that it overlays organic soils and, as discussed below, upward flowing groundwater (Figure 4). Previous evaluation of Delta soils did not fully account for texture and hydraulic conductivity. Moreover, upward flowing groundwater in this area was not accounted for. The DPR is reanalyzing GWPAs and will publish revisions within about 2 years. The Delta GWPA area will be eliminated from future GWPA delineations.[57]

In 2000, the State Water Resources Control Board created a map showing areas where published hydrogeologic information indicated conditions that may be more vulnerable to groundwater contamination. They termed these areas "Hydrogeologically Vulnerable Areas." Figure 4 shows the areas delineated by the State Water Resources Control Board where their analysis indicated that geologic conditions allow recharge to underlying water supply aquifers at higher rates or volumes.

[54] HydroFocus, Inc. Dutch Slough Restoration Area Third and Fourth Quarters 2012 Annual Groundwater Monitoring Report March 27, 2013.
[55] See footnote 52
[56] Troiano, John, Spurlock, Frank, Marade, Joe, 1999, Update of the California Vulnerability Soil Analysis for Movement of Pesticides to Groundwater, October 14, 1999, State of California Environmental Protection Agency, Department of Pesticide Regulation, http://www.cdpr.ca.gov/docs/emon/pubs/ehapreps/eh0005.pdf
[57] Personal oral communication by phone with John Troiano, April 2, 2015.

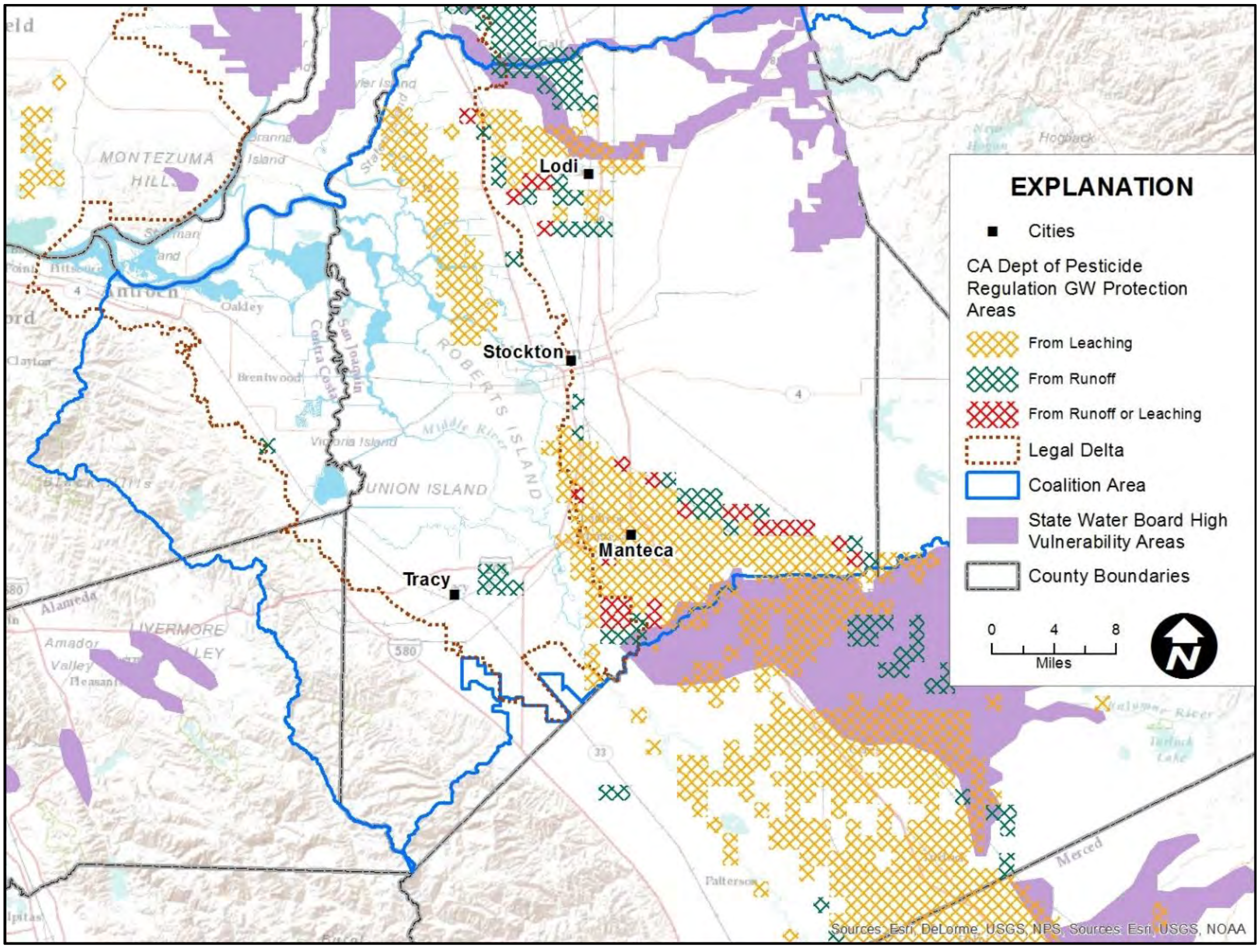

Figure 4. Distribution of Department of Pesticide Regulation Groundwater Protection Areas and Hydrogeologic Vulnerability Areas defined by the State Water Resources Control Board.

Monitoring

There are five primary existing groundwater quality data collection efforts as follows. First, the Pesticide Contamination Prevention Act enacted in 1985 provides mechanisms that strengthen Department of Pesticide Regulation's (DPR) regulatory authority to prevent ground water contamination and to respond to detections of pesticide residues in ground water. This Act obligated DPR to maintain a statewide database of wells sampled for pesticide active ingredients. DPR utilizes a network of about 3,000 municipal and domestic drinking water wells to characterize the spatial and temporal variability of groundwater pesticide and pesticide-metabolite concentrations throughout the State. In San Joaquin County, 75 wells were sampled during 2009 and 2010.

Second, California Department of Public Health monitors drinking water quality of domestic and municipal wells. In San Joaquin County, about 322 water supply systems are monitored. Third, since 1971, San Joaquin County Flood Control and Water Conservation District has monitored and published groundwater levels in over 550 wells. Two-hundred and seventy wells are monitored by County staff. Cooperating agencies also provide water level data. Limited water quality data has been collected from selected wells for chloride, electrical conductivity, and total dissolved solids concentrations.

Recently, the USGS has collected water quality data within San Joaquin County as part of the Groundwater Monitoring and Assessment Program and the evaluation of saline waters. Lastly, CDWR also collects groundwater level data within San Joaquin County and the Delta.

Methods and Data Sources

Non-Delta Area

Database and Geographic Information System

We created a Microsoft Access database to store and manage data related to wells and groundwater. The core of the database is a table containing a unique list of over 1,400 wells for which we obtained water quality and/or water level data. This table also contains general well-specific information, such as land surface elevation, depth, date drilled, and various water quality, water level, and lithologic data for the wells. Data for depth of wells were obtained from the USGS, CDWR and San Joaquin County. Wells in the Coalition Service Area are identified as either Delta or non-Delta.

The database contains several other data tables linked to the main table by well name. The water quality data table contains all of the date-referenced groundwater constituent concentration and water quality parameter data. The water-level data table contains date-referenced groundwater level data as depth-to-water from land surface, depth-to-water from a reading point other than land surface (with corresponding reading point elevation), and water level elevation referenced to sea level (with a specified vertical datum). The coordinates table contains geographic X and Y coordinates and specifies a horizontal datum (if reported by the source agency). The database also contains various well location properties derived through the GIS analysis. These include soil type and texture, land use, annual recharge rates from the USGS Central Valley Hydrologic Model (CVHM),[58] and subsurface textures from the CVHM texture model.

The Geographic Information System (GIS) is another key tool for data processing, analysis and management. The GIS database contains data layers for mapping that include relevant basic political and physical geographic features, such as river channels, cities, Coalition Service Area boundaries, and county boundaries. In addition we have incorporated geo-referenced (assigned locations referenced to a datum) information derived from our database, including groundwater concentrations of various constituents and parameters from 1969-2013 and seasonal depth-to-water and groundwater elevation data. The GIS database also includes various geo-referenced land properties: land use, soil type and texture, CVHM annual recharge rates, CVHM subsurface textures at various depth intervals, and San Joaquin County dairy locations.

[58] See footnote 4.

Water Quality Data

The database contains over 392,000 groundwater quality data points from the Coalition Service Area obtained from an array of sources. We obtained most of the data from the Groundwater Ambient Monitoring and Assessment Program (GAMA),[59] which is an inter-agency database maintained by the State Water Resources Control Board. Our database contains almost 343,000 GAMA values for 43 constituents and water quality parameters. We also obtained over 6,100 chloride, total dissolved solids, and electrical conductivity data points from San Joaquin County.[60] In reviewing the GAMA data, we identified several locations where groundwater nitrate concentrations exceeded the MCL that were associated with hazardous waste sites that were clearly not due to irrigated agriculture. These data were eliminated from the datasets used to delineate HVAs and are shown and locations mapped in the appendix.

The California Department of Pesticide Regulations was a source of over 11,000 data points for several pesticides, most prominently DBCP and EDB.[61] Over 18,000 data points with 38 constituents and parameters were obtained from the National Water Information System (NWIS) database maintained by USGS.[62] Finally, the CDWR Water Data Library was a source of over 13,600 data points consisting of 50 constituents and parameters.[63]

We received shallow groundwater quality data from the Dairy Cares Representative Monitoring Program (RMP) in the Coalition Service Area.[64]

The major ion composition of 1,662 well samples in the database were displayed and evaluated in a trilinear diagram. A trilinear diagram shows the proportions of the major cations (calcium, magnesium, and sodium plus potassium) and the major anions (carbonate plus bicarbonate, sulfate, and chloride) on a charge-equivalent basis[65]. We assessed the quality of major ion data by performing charge balance calculations. For each of the 3,008 groundwater samples from which we had concentrations of all major ions, we determined the sum of cation and anion charges in milliequivalents per liter.

The charge balance was calculated as the percentage relative error between the two sums:

$$\frac{Anions - Cations}{Anions + Cations}\ x\ 100$$

We classified the samples by varying degrees of quality according to the absolute value of the ion imbalance. The highest-quality samples were those with ion balance error less than 5%, comprising 1,662 of the major-ion samples. The intermediate-quality samples were those with ion balance error between 5 and 10%, comprising 955 of the major-ion samples. Finally, the samples deemed to have the lowest quality were those with ion balance error greater than 10%, which comprised 391 of the major-ion samples.

[59] http://www.swrcb.ca.gov/gama/geotracker_gama.shtml

[60] Electronic mail correspondence with Gerardo Dominguez of San Joaquin County Public Works.

[61] Electronic mail correspondence with Craig Nordmark of the California Department of Pesticide Regulations.

[62] http://waterdata.usgs.gov/nwis

[63] http://www.water.ca.gov/waterdatalibrary/

[64] Electronic mail correspondence with Till Angermann of Luhdorff and Scalmanini Consulting Engineers.

[65] Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254

We used boxplots to display the relation of nitrate concentrations to land use. Boxplots display the main data features and allow for comparison of groups of data[66]. For figures containing boxplots, the caption provides an explanation of the various components. The inner quartile (75%) of the data is displayed as a rectangle and the median value is denoted by a horizontal line within the rectangle. Lines extending vertically from the rectangle delineate 90% of the data. Asterisks denote outliers.

Water-Level Data

Our database also contains over 50,000 Coalition Service Area groundwater level data points in the form of depth-to-water and/or groundwater elevation referenced to sea level. San Joaquin County provided these data upon request[67]. The CDWR was also a source of water-level data in:1) a master file of water level data collected as part of the GAMA program from 2005 to 2010,[68] containing almost 9,900 water level data points from 421 wells and b) CASGEM, an internet data portal maintained by CDWR. Though much of the data available at CASGEM overlapped with data from GAMA, the former was a source for over 1,200 water level data points from 25 wells. Finally, we obtained almost 2,000 data points from 452 wells through the USGS NWIS database.

Land Use, Soils, Subsurface Lithology Well Information

Land Use

Geo-referenced land use data were obtained from the CDWR's county-wide soil surveys conducted in San Joaquin (1988, 1996) and Stanislaus (2004) counties, and the Delta (2007).[69] We also obtained data from the U.S. Department of Agriculture (USDA) that used satellite imagery to delineate land use. We obtained GIS data from the California Department of Conservation Farmland Mapping and Monitoring Program (FMMP) to identify the extent of irrigated agriculture in the Coalition Service Area. Locations given the following designations in 2012 were assumed to be irrigated areas: Prime Farmland, Unique Farmland, Farmland of Statewide Importance, and Farmland of Local Importance. All other land use categories (Grazing Land, Urban and Built-Up Land, Water, and Other) were regarded as non-irrigated areas.

In order to account for land use as a possible explanatory variable for groundwater nitrate concentrations, we assigned a fertilizer application rate to each well, based on the land use of the parcel on which the well is located. Land uses were determined based on CDWR land use surveys of the Sacramento-San Joaquin Delta (2007), San Joaquin County (1996), and Stanislaus County (2004).
We derived nitrogen application rates from a combination of California crop-specific rates found in the literature (Rosenstock and others[70], Li and others[71], and Viers and others[72]). Rosenstock and others

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[66] Minitab Reference Manual, 1989, Minitab Inc., Valley Forge, PA.
[67] Electronic mail correspondence with Gerardo Dominguez of San Joaquin County Public Works.
[68] Eric Senter (CDWR), via Francisca Johnson of Michael Johnson, LLC, through electronic mail correspondence.
[69] http://www.water.ca.gov/landwateruse/lusrvymain.cfm
[70] Rosenstock TS, Liptzin D, Six J, and Tonich TP. 2013. Nitrogen fertilizer use in California: Assessing the data, trends and a way forward. *California Agriculture* 67(1): 68-79.
[71] Li C, Six J, Horwath WR, Salas W. 2014. Final Report for Project Calibrating, Validating, and Implementing Process Models for California Agriculture Greenhouse Gas Emissions. Contract Number: 10-309.
[72] Viers JH, Liptzin D, Rosenstock TS, Jensen VB, Hollander AD, McNally A, King AM, Kourakos G, Lopez EM, de la Mora N, Fryjoff-Hung Am Dzurella KN, Canada H, Laybourne S, McKenney C, Darby J, Quinn JF, Harter T. 2012. Nitrogen Sources and Loading to

provided a compilation of crop-specific nitrogen fertilizer rate guidelines recommended by University of California Agricultural and Natural Resources, as well as average rates of overuse found for California in 2005. We summed the two to arrive at an estimate fertilizer usage rates. Li and others provided measured fertilizer application rates from specific field sites in Colusa, Napa, Solano, and Yolo counties.

Viers and others provided crop-specific rates of applied nitrogen fertilizer from various years since 1945; we used the values from 2005. Each study provided rates for a different set of crops. Where more than one of the studies included rates for a given crop, we used the median of the provided rates.
For some of the CDWR land use subclasses, none of the three studies provided a fertilizer application rate. For these, as well as the 'Unspecified,' 'Mixed,' and 'Miscellaneous' categories, we used each study's averages of provided rates within the same CDWR land use class. For instance, for the subclass 'Unspecified' within the class 'Deciduous Fruits and Nuts,' we used the median of the following three values: (1) the average of Rosenstock's rates from crops within the 'Deciduous Fruits and Nuts' class, (2) the only 'Deciduous Fruits and Nuts' crop rate specified by Li ('almonds'), and (3) the average of Viers' provided rates from crops within the 'Deciduous Fruits and Nuts' class. We assigned the fertilizer application rates found in Table 3 to the associated land use in GIS. We were then able to assign a fertilizer application rate to each well based on the land use associated with the well location.

Table 3. Nitrogen fertilizer application rates by land use.

CDWR Class	CDWR Subclass	Application Rate lb N ac^{-1} yr^{-1}
Deciduous Fruits and Nuts	Almonds	221
Deciduous Fruits and Nuts	Apples	74
Deciduous Fruits and Nuts	Apricots	117
Deciduous Fruits and Nuts	Cherries	84
Deciduous Fruits and Nuts	Miscellaneous deciduous	145
Deciduous Fruits and Nuts	Peaches and nectarines	128
Deciduous Fruits and Nuts	Pears	174
Deciduous Fruits and Nuts	Unspecified	145
Deciduous Fruits and Nuts	Walnuts	180
Field Crops	Beans, dry	101
Field Crops	Corn	264
Field Crops	Safflower	126
Field Crops	Sudan	272
Field Crops	Sugar beets	193
Field Crops	Unspecified	185
Grain and Hay Crops	Miscellaneous and mixed grain and hay	141
Grain and Hay Crops	Unspecified	141
Idle Farmland	—	0
Pasture	Alfalfa and alfalfa mixtures	19
Pasture	Mixed pasture	19
Pasture	Native pasture	19
Pasture	Turf farms	218
Pasture	Unspecified	19
Rice	Unspecified	144
Semiagricultural and Incidental to Agriculture	Dairies	423
Semiagricultural and Incidental to Agriculture	Farmsteads	0
Semiagricultural and Incidental to Agriculture	Livestock feed lots	423
Semiagricultural and Incidental to Agriculture	Poultry farms	423
Semiagricultural and Incidental to Agriculture	Unspecified	0
Truck, Nursery, and Berry Crops	Asparagus	174
Truck, Nursery, and Berry Crops	Beans, green	229
Truck, Nursery, and Berry Crops	Bush berries	255
Truck, Nursery, and Berry Crops	Flowers, nursery, and Christmas tree farms	228
Truck, Nursery, and Berry Crops	Melons, squash, and cucumbers	171
Truck, Nursery, and Berry Crops	Miscellaneous truck crops	229
Truck, Nursery, and Berry Crops	Mixed	229

CDWR Class	CDWR Subclass	Application Rate lb N ac^{-1} yr^{-1}
Truck, Nursery, and Berry Crops	Onions and garlic	282
Truck, Nursery, and Berry Crops	Peppers	297
Truck, Nursery, and Berry Crops	Tomatoes	229
Truck, Nursery, and Berry Crops	Unspecified	229
Vineyards	Unspecified	43
Vineyards	Wine grapes	43

We assessed water quality risks to disadvantaged communities (DACS) and disadvantaged unincorporated communities (DUCS) dependent on groundwater. Two sources of information were considered. First, communities deemed 'disadvantaged' based on 2013 median household income (MHI) data obtained from the US Census Bureau were incorporated into the GIS. Following the definition provided by the California Environmental Protection Agency,[73] a census-designated place (CDP) was categorized as 'disadvantaged' if its MHI is less than 80% of the statewide average. Disadvantaged CDPs in the Central Valley portion of the Coalition Service Area are August, Country Club, Farmington, French Camp, Garden Acres, Kennedy, Lockeford, Lodi, Stockton, Taft Mosswood, Thornton, Valley Home, and Victor. Second, identified and potential DUCs were delineated using data provided by Policy Link[74] and these locations were incorporated in the GIS. We have classified the Delta as low-vulnerability due to its hydrologic conditions. Thus any Delta DACs and DUCs (there were three potential DUCs in the northern Delta) have been excluded from the map displayed in Figure 23.

Soils

Geo-referenced soil data were obtained from the USDA Natural Resource Conservation Service (NRCS) soil surveys of San Joaquin and northern Stanislaus counties.[75] In the non-Delta portion of the Coalition Service Area, textural composition was used to estimate and map the percent sand in soils. Specifically, we used the soil textural triangle shown in Figure 5 to estimate the percent sand throughout the Coalition Service Area by estimating the sand percentage mid-range percent value for each soil series. This value was assigned to each well in the non-Delta portion of the Coalition Service Area. In the Delta, we included a map of organic and highly organic mineral soils using data described in Deverel and Leighton[76]. We also obtained soil pH and salinity data for San Joaquin and Stanislaus counties.

Subsurface Lithology and Groundwater Supply Information

The first source of information about subsurface lithology was a collection of well logs within the Coalition service area provided by CDWR. Out of the nearly 19,000 logs received, we identified 370 corresponding to water quality and/or water level data available in the CDWR Water Data Library. Each

[73] California EPA, "Financial Assistance Programs – Grants and Loans," http://www.waterboards.ca.gov/water_issues/programs/grants_loans/small_community_wastewater_grant/index.shtml.Accessed January 30, 2015.
[74] PolicyLink, 2013, California Unicoporated: Mapping Disadvantaged Communities in the San Joaquin Valley, http://www.policylink.org/sites/default/files/CA_UNINCORPORATED_2.PDF. Accessed March 30, 2015.
[75] http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm
[76] See footnote 28.

well log contains subsurface lithology information from ground surface to the bottom of the borehole, as well as the depth intervals where the well is screened.

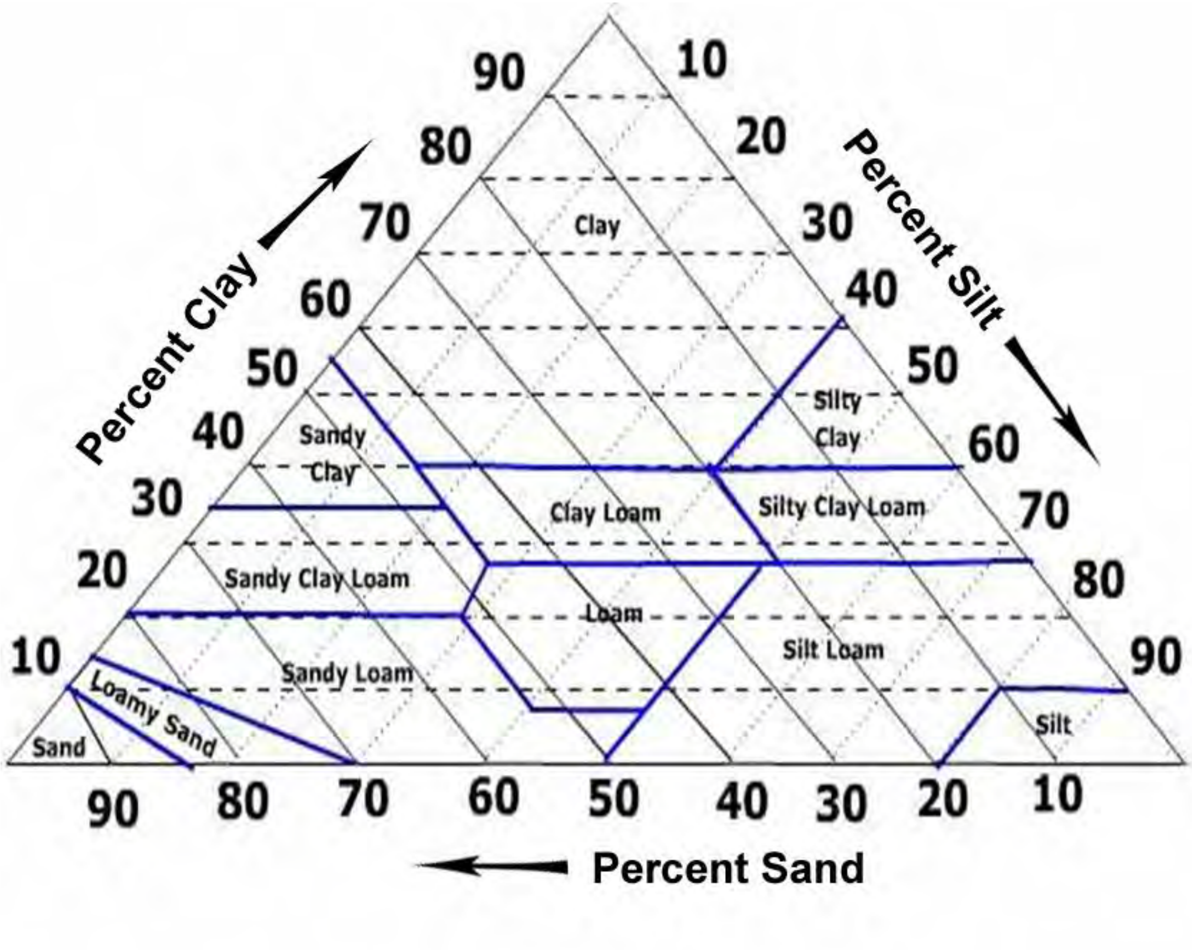

Figure 5. Soil textural triangle.

The second source of subsurface geological information was the texture model developed as part of USGS CVHM effort[77]. The texture model represented 50-foot depth intervals to a depth of 2,800 feet below land surface. Texture was quantified as the coarse-grain fraction. The coarse-grain fraction includes sand, gravel, pebbles, boulders, cobbles, and conglomerate. The textural distribution is quantified on one-mile square grid for the entire Central Valley.

To extract the appropriate textural data from the CVHM, we obtained information on screened intervals for municipal supply wells in the cities of Lodi, Lathrop, and Ripon.[78] Because the bulk of these supply wells are screened within 300 feet of land surface, we limited our use of the CVHM texture model to the first 300 feet of depth in keeping with the goal of characterizing risks to public drinking water quality. Texture data from the CVHM were provided in cell-by-cell tabulated form, also as a part of the model file download. Therefore, each well was associated with a textural value (percent coarse-grained). These were appended to the CVHM grid layer and clipped to the Coalition Service Area for use in texture map figures.

We obtained GIS files on public water systems (PWS) from the California Department of Public Health (CDPH), including attributes that we used to determine which PWS in the Coalition Service Area supply drinking water and rely on groundwater.

Groundwater Recharge

Gross and net groundwater recharge rate (deep percolation minus pumping) estimates were extracted from the CVHM. The CVHM makes use of a module called the Farm Process, which uses a hydrologic balance to calculate recharge rates based on crop water demands, rates of precipitation and evapotranspiration, and surface water irrigation supply.[79] Net recharge data were extracted and aggregated annually from CVHM output files using a FORTRAN program. These were then appended to a GIS layer of the CVHM grid, which was provided by the USGS with the model files.[80] We also developed a FORTRAN program to extract the spatially variable pumping volumes from the CVHM groundwater pumping file for calculation of net recharge.

Particle Tracking

We utilized the CVHM and a particle-tracking post processor (MODPATH) to delineate areas that contribute groundwater recharge to public water systems (PWS) dependent on groundwater. Most of these PWS include or are located near disadvantaged communities. The CVHM is based on MODFLOW[81], and is a transient representation of the Central Valley Aquifer, California groundwater

[77] See footnote 4.
[78] Electronic mail correspondences with Larry Parlin (City of Lodi), Greg Gibson (City of Lathrop), and Ted Johnston (City of Ripon).
[79] Schmid, Wolfgang, R.T. Hanson, Thomas Maddock III, and S.A. Leake. 2006. User guide for the Farm Process (FMP1) for the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, MODFLOW-2000: U.S. Geological Survey Techniques and Methods 6-A17, 127 p. (Also available at http://water.usgs.gov/nrp/gwsoftware/mf2k-fmp/mf2kfmp.html.)
[80] http://ca.water.usgs.gov/projects/central-valley/central-valley-hydrologic-model.html
[81] Harbaugh and others, "MODFLOW-2000: U.S. Geological Survey Modular Ground-Water Model—User Guide to Modularization Concepts and the Ground-Water Flow Process," U.S. Geological Survey Open-File Report 00–92, 2000.

system.[82] The simulated area is represented by ten layers of 1 mile-square model cells, and the model simulates monthly water level and groundwater storage changes during the period 1961-2003.

The simulated flow conditions were assessed using the post-processor MODPATH[83], which computes the migration of water particles through the groundwater system. The program calculates groundwater velocities by dividing groundwater flow by porosity. The porosity distribution was represented using the percentage of coarse-grained sediment specified for each CVHM cell. The resulting porosity values average about 40% (the average porosity by layer ranges from 40 to 43%).

Recharge areas contributing to PWS wells were delineated by first placing particles in model cells representing the recent (2003) PWS groundwater supply. Available water supply well data indicated that the depth interval of well screens typically range from about 170 to 400 feet below land surface, which generally corresponds to the depth interval represented by model layer 3 (150 to 300 feet below land surface). Particles were placed initially in all layer 3 model cells that underlie the PWS, and then back-tracked to determine their migration to locations corresponding to the start of the simulation (1961). These ending locations identify the various recharge areas that contributed to the PWS groundwater supply during the 42-year simulation period.

Mapping and Vulnerability Assessment Methods

We used ArcGIS to plot wells from our database for the purposes of visual display and creating map figures. In addition, ArcGIS was used for analyzing other geo-referenced data in our GIS files. We were thus able to assign various geographically based characteristics (soil type, land use, recharge, etc.) to all wells, enabling us to statistically analyze their relationships with water quality data and better understand the variables affecting nitrate concentrations.

To assign vulnerability of groundwater to degradation due to irrigated agriculture, we employed a 4-step approach. First, we used the ArcGIS Spatial Analyst and the statistical program MINITAB to calculate nitrate regression model results on a cell-by-cell basis with 330-square-foot resolution, so as to geospatially display calculated groundwater nitrate concentrations based on the regression model results. Second, we use ArcGIS Geostatistical Analyst to perform indicator kriging (see description below) to estimate the probability that groundwater nitrate concentrations are greater than or less than a threshold value. Third, we used the results of particle tracking to delineate contributing areas to communities that use groundwater and disadvantaged communities. Lastly, we used ArcGIS Spatial Analyst to develop a system to evaluate and delineate areas with varying potential for groundwater contamination using the DRASTIC methodology[84]. Table 4 shows the factors used for the four methods.

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[82] See footnote 4.

[83] Pollock, David W., "User's Guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the U. S. Geological Survey finite-difference ground-water flow model," U.S. Geological Survey Open-File Report 94-464.

[84] Aller, L., Bennet, T., Lehr, J.H. and Petty, R.J., 1987, DRASTIC: a standardized system for evaluating groundwater pollution potential using hydrogeologic settings. U.S. EPA Report 600/2-85/018)

Table 4. Characteristics used in the four methods for delineating HVAs.

Characteristics Used to Evaluate Vulnerability	Nitrate Regression Model	Kriging	Particle Tracking	DRASTIC Model
Existing NO3 Data	X	X		
Land Use	X			
Groundwater Flow			X	
Soil and Vadose-zone Characteristics	X		X	X
Depth to Groundwater	X			X
Recharge	X		X	X
Topography				X
Hydraulic Conductivity			X	X

Indicator Kriging

We used indicator kriging within the ArcGIS Geostatistical Analyst to create maps that estimate the probability that groundwater nitrate concentrations are greater than or less than a threshold value[85]. Indicator kriging has been used in multiple locations for assessing the risk of soil or groundwater contamination and the distribution of suitability of groundwater quality for irrigation[86].

[85] Alley, William M., 1993, Geostatistical Methods in (William, M. Alley, ed) Regional Characterization of Groundwater Quality, Van Nostrand Reinhold, New York.
See also chapter 22 in this book by Dubrovsky, Deverel and Gilliom on selenium in the San Joaquin Valley
[86] Example publications where indicator kriging have been used for groundwater quality include the following:
Goovaerts P, AvRuskin G, Meiliker J, Slotnick M, Jacquez G, Nriagu J, 2005, Geostatistical modeling of the spatial variability of arsenic in groundwater of southeast Michigan. Water Resources Research 41:1–19.

Chica-Olmoa, Mario, Luque-Espinarb, Juan Antonio, Rodriguez-Galianoc, Victor, Pardo-Igúzquizad, Eulogio, Chica-Rivase, Lucía, 2014, Categorical Indicator Kriging for assessing the risk of groundwater nitrate pollution: The case of Vega de Granada aquifer (SE Spain), Science of The Total Environment, volumes 470–471: 229–239.

Sheikhy Narany, Tahoora, Firuz Ramli, Mohammad, Aris, Ahmad Zaharin, Nor Azmin Sulaiman, Wan and Fakharian, Kazem, 2014, Spatial assessment of groundwater quality monitoring wells using indicator kriging and risk mapping, Amol-Babol Plain, Iran, Water, 6, 68-85.
These authors identified areas with a high risk of nitrate pollution for the Amol-Babol Plain, Iran. The indicator kriging method was applied to identify regions with a high probability of nitrate contamination using data obtained from monitoring wells.

Dash, J. P. Sarang, A. I, Singh, D. K., 2010, Spatial Variability of Groundwater Depth and Quality Parameters in the National Capital Territory of Delhi, Environmental Management (2010) 45:640–650.
Indicator kriging was used to estimate probability of exceedances for groundwater quality parameters (chloride, electrical conductivity, fluoride, magnesium, and nitrate).

Delbari , Masoomeh, Amiri, Meysam and Bahraini Motlagh, Masoud, 2014, Assessing groundwater quality for irrigation using indicator kriging methods, Applied Water Science, 10.1007/s13201-014-0230-6 .
The spatial variability of groundwater quality parameters (EC, SAR, Na+, Cl−, HCO3 − and pH) was investigated using geostatistical methods to determine the most suitable groundwater quality areas for implementation of sprinkler irrigation systems.

For indicator kriging, the data are transformed into either zeroes or ones depending on whether they are greater than or less than a specified threshold. The transformed data values are used as input to ordinary kriging and the indicator kriging predication at a location is the probability that the threshold is exceeded[87].

Statistical Analysis

We used multiple linear regression[88] to assess processes and factors affecting nitrate concentrations. The regression process determines the best fit among a dependent variable (nitrate concentrations) and independent variables (land use, depth to groundwater, recharge, subsurface texture, etc.). We experimented with multiple models to maximize the level of variance in nitrate concentrations explained by the dependent variables.

We used non-parametric comparative statistical techniques to evaluate differences in groundwater nitrate concentrations among land uses. These included the Kruskal-Wallis and the Mann-Whitney tests[89]. The Kruskal-Wallis method offers a non-parametric alternative to the one-way analysis of variance. The test assumes that the data arise as independent random samples of continuous distributions. The null hypothesis of no difference in nitrate concentrations among land used is tested against the alternative of at least one difference. The Mann-Whitney method tests the differences between two populations and was used here to assess the difference in nitrate concentration among two land uses.

We used the SANITAS™ (version 9.4) statistical software package to analyze temporal trends in the analytical results for samples collected from the monitoring network wells. The software performs statistical procedures consistent with federal (EPA) and state regulations. Temporal trends were evaluated using the Mann-Kendall test with a significance level of 0.05. The Mann-Kendall test is a nonparametric test used to determine if the trends in constituent concentrations over time are statistically significant. We also used SANITAS software to identify outlier values in wells with multiple samples collected over time.

DRASTIC Methodology for Calculating an Index of Intrinsic Susceptibility

DRASTIC is a widely used index model used to assess vulnerability to groundwater contamination for alluvial basins. As input, the model uses seven physical properties contributing to intrinsic susceptibility to downward transport of contaminants from land surface to the saturated zone. The model output is a two-dimensional map of susceptibility indices which delineate areas with relatively higher and lower vulnerability.

Spatially referenced properties that influence movement of contaminants to groundwater used by DRASTIC are depth to groundwater (D), net annual recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and aquifer hydraulic conductivity (C). For each property,

[87] Konstantin Krivoruchko, 2011, Spatial Statistical Data Analysis for GIS Users, ESRI Press, 928 pp.
[90] Steele, R.G.D and Torries, J.H., 1960. Principles and Procedures of Statistics, McGraw Hill.
[91] ibid

a rating (R) and a weight (W) are determined according to tables supplied by Aller and others[90]. Ratings range from 1 to 10, the latter represents the highest degree of contamination vulnerability. Weights correspond with each property's relative importance in driving groundwater vulnerability (Table 5). The index (DI) is calculated as:

$$\boldsymbol{DI = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W} \qquad (\mathbf{1})$$

We also used the DRASTIC pesticide (sometimes referred to as agricultural DRASTIC) to assign weightings and scores for the 7 DRASTIC parameters (Table 5). The key differences between the two approaches are the weights for soil media (5 versus 2), topography (3 versus 1), impact of the vadose zone (5 versus 4) and hydraulic conductivity (3 versus 2) (Table 5). The increased weight for soil media increases the importance of coarse-textured soils which results in higher scores.[91]

[90] See footnote 86

[91] Some researchers have compared DRASTIC and DRASTIC pesticide scores. Examples include the following.
Al-Zabet, T., 2002, Evaluation of aquifer vulnerability to contamination potential using the DRASTIC method, Environmental Geology (2002) 43:203–208.
.T. D. Albuquerque & G. Sanz & S. F. Oliveira & R. Martínez-Alegría & I. M. H. R. Antune, 2013,, Spatio-Temporal Groundwater Vulnerability Assessment - A Coupled Remote Sensing and GIS Approach for Historical Land Cover Reconstruction, Water Resources Management, 27:4509–4526
Ahmed, Ayman A., 2009, Using Generic and Pesticide DRASTIC GIS-based models
for vulnerability assessment of the Quaternary aquifer at Sohag, Egypt, Hydrogeology Journal, 17: 1203–1217

Table 5. Assigned Weights for standard and pesticide DRASTIC features

Feature	Weight	
	Standard DRASTIC	Pesticide DRASTIC
Depth to groundwater (D)	5	5
Recharge (R)	4	4
Aquifer media (A) (shale, sandstone, sand and gravel, etc.)	3	3
Soil media (S) (sand, loam, clay, etc.)	2	5
Topography (T) (percent slope)	1	3
Impact of vadose zone (I) (ratings based on soil texture	5	4
Aquifer hydraulic conductivity (C)	3	2

The DRASTIC model has been used worldwide to classify the spatially-variable susceptibility of aquifers to pollution for a variety of pollutants during the last 25 years. For example, Fritich and others[92] used DRASTIC to assess the groundwater pollution in Central Texas and correlated high groundwater nitrate concentrations with areas with high DRASTIC scores. Where there were oxidizing conditions, Mishima and others[93] reported DRASTIC scores correlated with groundwater nitrate concentrations. Aydi and others[94] reported correlation between groundwater nitrate concentrations and DRASTIC scores. Babiker and Kato[95] successfully used the DRASTIC model to assess groundwater nitrate pollution potential in Japan. Other authors have evaluated the general vulnerability of aquifers to pollution using DRASTIC[96] and specific pollutants such as VOCs[97] and trace metals[98].

For our use of DRASTIC, we developed GIS raster grids for each of the seven input properties, with each property specified on a pixel-by-pixel basis across the Coalition Service Area. We then used GIS tools to calculate the DRASTIC index for each pixel. Description of the individual input properties follows.

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[92] Frtitch, T.G., McKnight, C.L., Yelderman, J.C., Dworkin, S.I., Arnold, J.G., 1999, A predictive modeling approach to assessing the groundwater pollution susceptibility of the Paluzy Aquifer, Central Texas, using a Geographic Information System, Environmental Geology 39 (9) July

[93] Yoshio Mishima, Masayuki Takada ,Rie Kitagawa, 2011, Evaluation of intrinsic vulnerability to nitrate contamination of groundwater: appropriate fertilizer application management, Environ Earth Sci (2011) 63:571–580

[94] Wanissa Aydi. Salwa Saidi, Moncef Chalbaoui, Soumia Chaibi, Hamed Ben Dhia, 2013, Evaluation of the Groundwater Vulnerability to Pollution Using an Intrinsic and a Specific Method in a GIS Environment:Application to the Plain of Sidi Bouzid (Central Tunisia), Arab J Sci Eng (2013) 38:1815–1831

[95] Babiker, Mohamed, Tetsuya, Kato, 2005, A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan, Science of the Total Environment 345 (2005) 127-140.

[96] Ersoy, A.F., Gültekin, Fatma, 2013, DRASTIC-based methodology for assessing groundwater vulnerability in the Gümüşhacıköy and Merzifon basin (Amasya, Turkey), Earth Sci. Res. SJ. Vol. 17, No. 1 (June, 2013): 33 - 40

[97] E.g. Kalinski, R.J., W.W. Kelly, I. Bogardi, R.L. Ehrman, and P.D. Yamamoto. 1994. Correlation between drastic vulnerabilities and incidents of VOC contamination of municipal wells in Nebraska. Ground Water 32:31 -34.

[98] Ronaldo Herlinger Jr Æ Antonio Pedro Viero, 2007, Groundwater vulnerability assessment in coastal plain of Rio Grande do Sul State, Brazil, using drastic and adsorption capacity of soils, Environ Geol (2007) 52:819–829

Depth to Water

Depth to groundwater ("D") from land surface is an important determinant of groundwater vulnerability. The further that infiltrating water has to travel before reaching the water table, the higher the likelihood that solute contaminants will be attenuated in the subsurface before reaching groundwater. To create a depth-to-water raster, we first calculated the average value for each water level well in our database. In order to account for long-term water level trends, recent data were used for averaging: 1989-2013 for the Delta, and 2009-2013 for non-Delta. We then performed a spatial interpolation of depth-to-water from these point values to obtain a raster for the whole study area. Table 6 below shows the depth-to-water ratings used.

Table 6. Depth to groundwater ratings (D)

Range (ft)	DRASTIC Rating
0 – 5	10
5 – 15	9
15 – 30	7
30 – 50	5
50 – 75	3
75 – 100	2
> 100	1

Net Recharge

Net recharge ("R") refers to the net amount of water (i.e., deep percolation minus pumping) that travels downward from the surface to the saturated zone. This downward infiltration acts as a vehicle for introducing surface contaminants to the groundwater system, so high vulnerability is associated with high net recharge rates. Annual net recharge figures were obtained from CVHM output files (as described above in "Methods and Data Sources"). For each model cell, we calculated an average net recharge rate across the time period represented by the model. We then converted these values into a finer raster grid for use in DRASTIC calculations, and reclassified values as shown in Table 7 below.

Table 7. Groundwater recharge ratings (R)

Range (in)	DRASTIC Rating
0 – 2	1
2 – 4	3
4 – 7	6
7 – 10	8
> 10	9

Aquifer Media

Aquifer media ("A") is related to the geologic nature of aquifer materials through which groundwater flows. It pertains to contamination vulnerability because aquifer media with larger pore volumes afford greater opportunity for attenuation of contaminants. Of the aquifer media categories identified and rated by Aller and others, the only one existing in the Coalition study area is "Sand and Gravel," with a typical rating of 8. We assigned this value uniformly across the DRASTIC model area, so ultimately aquifer media did not play a part in determining relative groundwater vulnerability.

Soil Media

The soil media ("S") component characterizes the uppermost layer of the unsaturated zone.[99] Soil texture plays a significant role in determining the ability of a surface contaminant to infiltrate into the subsurface. Coarser-grained materials correspond with higher groundwater vulnerability. For each NRCS soil texture present in the study area, we identified the best-matching texture type in the categories provided by Aller and others. Table 8 below shows the values used.

Table 8. Soil texture ratings.

Soil Texture	Rating
Thin or Absent	10
Gravel	10
Sand	10
Peat	8
Shrinking and/or Aggregated Clay	7
Sandy Loam	6
Loam	5
Silty Loam	4
Clay Loam	3
Muck	2
Nonshrinking and Nonaggregated Clay	1

Topography

Local topography ("T") impacts the ability of a contaminant to enter the subsurface. Surface water runoff occurs more readily in locations with high slopes, whereas low slopes cause water to stay in place and infiltrate. We obtained ground elevation raster grids from the USGS National Elevation Dataset (NED), and then used GIS tools to calculate percent slope on a pixel-by-pixel basis. We then classified slope ranges and assigned ratings for the property according to the categories in Table 9 below.

[99] Aller and others (1987), 45.

Table 9. Topography ratings

Range (% Slope)	Rating
0 – 2	10
2 – 6	9
6 – 12	5
12 – 18	3
> 18	1

Impact of Vadose Zone

The vadose zone media (”I”) impacts contamination vulnerability by way of path lengths and the ability for contaminants to attenuate in the subsurface. Aller and others provide ranges of ratings for ten categories of vadose zone media. Silt/clay and sand and gravel occur in the subsurface of the Coalition Service Area. We used the shallowest 50-foot segment of the CVHM texture model to represent vadose zone texture. The texture model provides a distribution of percent coarse-grained material within each model cell. Rather than losing exactness by converting percentage into one of the broad categories and rating ranges provided for DRASTIC, we applied a linear scale to associate the percentage with a rating, as shown below in Table 10. (There were no cells in the Coalition Service Area with > 90% coarse-grained material.) The CVHM cells with corresponding coarse-grained percentage were converted to a raster grid with pixel-by-pixel rating values.

Table 10. Vadose zone (I) ratings

Percent Coarse-Grained	Rating
0 – 10	1
10 – 20	2
20 – 30	3
30 – 40	4
40 – 50	5
50 – 60	6
60 – 70	7
70 – 80	8
80 – 90	9

Aquifer Hydraulic Conductivity

The aquifer hydraulic conductivity (“C”) represents the ease of water and contaminant transmission through saturated-zone flow. Locations with high underlying conductivity are more prone to receiving contaminants that may have entered the saturated zone. A FORTRAN program was used to extract cell-by-cell vertical and horizontal hydraulic conductivity values from CVHM input. In the part of the model overlaying the Coalition Service Area, the first four layers constitute approximately 300 feet of depth. For each CVHM planar cell, conductivity values from layers 1-4 were weighted by thickness and averaged. We created raster grids and classified their DRASTIC ratings based on the ranges shown in Table 11 below. We performed two different iterations of DRASTIC index calculations: one using horizontal conductivity values, and one using vertical. Differences in spatial distribution of DRASTIC ratings were negligible.

Table 11. Aquifer hydraulic conductivity (C) ratings.

Range (GPD/Ft^2)	Rating
1 – 100	1
100 – 300	2
300 – 700	4
700 – 1,000	6
1,000 – 2,000	8
> 2,000	10

Delta Areas

Land Surface Elevation

Maps showing land surface elevations for the portion of the Delta in the Coalition Service Area were created from LIDAR (Light Detection and Ranging) data collected by the California Department of Water Resources in January and February 2007. HydroFocus personnel downloaded and incorporated these data into the GIS database.

Lithology

To understand island hydrologic conditions, it is important to determine the bottom elevation and thickness of the tidal organic deposits. For the purposes of this report, we estimated the depth of the organic soil layer. To determine the bottom elevation of the organic deposits, we obtained well logs from the Delta Wetlands Project, the 2004 Jones Tract Flood Report, and from the CDWR. We used these data and data presented in Atwater[100] to define the bottom elevation of the peat. Using well and boring logs available from CDWR, Atwater posted 1,081 values for the bottom elevation of the peat on 24-minute USGS quadrangle maps. We digitized these points and incorporated the locations and values into the GIS database.

We also extracted the peat-bottom elevations from boring logs obtained from CDWR and published in the Delta Wetland Project reports from other projects throughout the Delta. These included the Alternative Delta Facilities Special Studies (1976), West Delta Temporary Barriers (1977), Hotchkiss Tract Sewage Collection System (1977), Evaluation of Levees at Aqueduct Crossing (1981), Woodward Island Supplementary Engineering Studies (1981), McDonald Island Piezometer Installation Report (1984), Brannan Levee Project (1987), Sherman Island Pipeline 131 Levee Stability Study (1987), Delta Wetlands

[100] Atwater, B.F. 1982. Geologic Maps of the Sacramento-San Joaquin Delta, U.S. Geological Survey, Miscellaneous Field Studies Map MF – 1401.

Project (1988), Hotchkiss Tract Treatment Plant Ponds (1988), Hotchkiss Tract PGE Pipeline Crossing (1990), North Fork Mokelumne River Setback Levees (1992), Webb Tract Levee Improvements 2000-2001 (2001), Jersey Island Triple Decker Project (2003), Bethel Island Liquidation Investigation Delta Coves (2003), Jersey Island Geotechnical Data (2004), Groundwater Monitoring Jones Tract Flood (2005), Webb Tract Geotechnical Investigation Stations 317 & 435 (2007),Holland Tract Levee Rehab Station 55 to 250 (2008), Sherman Island Landslide Setback Habitat Project (2008), and Bethel Island Horseshoe Bend (2011). Using the Atwater definitions for peat and mud bottoms, we extracted land surface, mud bottom, and peat bottom elevations from boring logs. The land surface elevation datum was either listed on the log or assumed to be NGVD 29. We merged these points with the Atwater points from the late-1970s to 2011. This resulted in 1,215 peat bottom elevation points. We converted all points to the vertical datum NAVD 88 using VERTCON[101].

We used the theory of regionalized variables or geostatistics and Geostatistical Analyst within ArcGIS to create an organic-deposit bottom elevation grid in GIS. The theory of regionalized variables relies on the description of data collected in geographic areas as randomly distributed[102].
The semivariogram (γ) is defined as

$$\gamma(h) = \frac{variance\left[z(x_i) - z\left(x_j\right)\right]}{2}$$

where:
h is the lag or average distance between data points and
z(x) is the elevation of the peat or mud bottom at location x

We therefore calculated the semivariogram to estimate the spatial covariance in the area of organic deposits shown in Figure 1 in Deverel and Leighton[103]. We then interpolated with kriging which uses a linear combination of weighting factors and measured values of $z\left(x_j\right)$ that minimizes the estimation variance. Plotting of the semivariogram can provide insight about the spatial distribution of a variable and the factors affecting its distribution.

Kriging, the process of interpolation from measured values of some variable z measured at N locations relies on the determination of the spatial covariance or semivariogram of the variable at points x_i… The objective of kriging for this study was to characterize the general spatial distribution of the peat- bottom elevations. We attempted to model the semivariograms that best represented data for a large geographic area for peat-bottom elevations. The directional spherical and exponential semivariograms normal to the maximum drift (north-south direction) showed the lowest sill variance and were used for kriging for the peat-bottom elevations. The semivariogram models were iteratively verified and refined to minimize the estimation variance for both variables. We calculated and plotted directional semivariograms to determine anisotropy. The west to east directional semivariogram showed the most drift, especially at greater distances. In contrast, the north to south direction showed the least drift.

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[101] http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html
[102] David, M. 1977. Geostatistical ore reserve. New York (NY): Elsevier Scientific
Journel, A.G. and Ch. J. Huijbregts. 1978. Mining Geostatistics. San Diego (CA): Academic Press Harcourt Brace & Company, Publishers. Matheron, G. 1963. Principles of Geostatistics. Economic Geology 58: 1246-1266.
[103] See footnote 28.

Groundwater and Surface Water Levels

To assess regional groundwater levels throughout much of the Coalition Service Area within the Legal Delta, we utilized multiple data sources. Surveyed measuring point elevations were reported for all these wells which we used to calculate the groundwater elevations relative to NGVD 29.

Delta Wetlands Project groundwater level data was collected from wells located on or near the levees throughout the Delta[104]. Data were presented in tabular format from 1989 to 1990. From 1990 through 1995, data were presented in graphs. We manually digitized the graphs and extracted the data. We used these data to calculate average groundwater elevations for each well. Approximate groundwater-level measuring point elevations were reported in the Delta Wetland Project documentation which we used to calculate the groundwater elevations relative to NGVD 29.

We also obtained groundwater level data measured by transducers every 15 minutes during 2004 and 2005 as part of the Upper Jones Tract flood monitoring[105]. We used surveyed groundwater-level measuring point elevations to calculate the groundwater elevations by subtracting the depth to water values from the reported elevation.

We used 2011 and 2012 data for two wells from the Dutch Slough groundwater monitoring project where water-level data was recorded every 15 minutes using transducers[106]. Average Twitchell Island manual groundwater level measurements from four wells from 2001 to 2013 were also used. We utilized groundwater level data collected on Jersey Island by HydroFocus personnel from 2006 to 2008. We downloaded water level measurements from a 57-foot deep USGS well on Medford Island with data from 1983 through 1987[107]. We obtained groundwater level data for Roberts Island from Water Associates Group[108] who has collected baseline data for potential ship channel dredge material disposal.

We obtained river stage data from ten gauge stations from 2009 to 2012. The stations are operated by CDWR and the USGS. Data were obtained from the California Data Exchange Center (CDEC)[109] and the CDWR Water Data Library.[110] For each station, we calculated daily average stage and average daily high water stage.

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[104] Harding Lawson Associates. 1991. A Report Prepared for Delta Wetlands: Groundwater Data Transmittal No. 2 Delta Wetlands Monitoring Program Sacramento-San Joaquin River Delta.
Hultgren-Tillis Geotechnical Engineers. 1995. Groundwater Data Transmittal No. 4 Delta Wetlands Project Sacramento-San Joaquin River Delta.
[105] Hultgren-Tillis Geotechnical Engineers. 2005. Groundwater Monitoring Jones Tract Flood Sacramento-San Joaquin Delta, California. Prepared for the Department of Water Resources, April 15, 2005.
[106] HydroFocus, Inc. 2013. Dutch Slough Restoration Area First and Second Quarters 2012 Groundwater Monitoring Report.
[107] Available online from USGS at
http://nwis.waterdata.usgs.gov/nwis/gwlevels/?site_no=380250121301601&agency_cd=USGS&
[108] Steve Michelson and Tyson Fulmer, Water Associates Group, written communication, 2013.
[109] Available online from CDWR at http://cdec.water.ca.gov/.
[110] Available online at http://www.water.ca.gov/waterdatalibrary/.

Water Isotope Data

In addition to the Twitchell Island chemical data presented in Deverel and others[111], HydroFocus collected groundwater water isotope data on Jersey Island and the Emerson, Gilbert and Burroughs parcels in the Dutch Slough area and Hotchkiss Tract, Bouldin Island, and Wright-Elmwood Tract. These data help illustrate the relation of groundwater and adjacent channels for islands within the Coalition Service Area.

Water isotope data or stable isotopes of hydrogen and oxygen are helpful in identifying water sources. The hydrogen and oxygen atoms that combine to form water molecules exist naturally in different forms (isotopes). Stable isotopes of hydrogen and oxygen, deuterium (D) and oxygen-18 (^{18}O), are not radioactive and do not change composition over time and, therefore can provide reliable information about water sources. Water molecules containing these isotopes are primarily $DH^{16}O$ and $H_2{}^{18}O$, which have larger atomic masses than the most abundant $H_2{}^{16}O$. The amount of D and ^{18}O in a water sample is represented by the Greek letter δ (delta) which is equal to the ratio of heavy to light isotopes in the sample relative to a standard. In the case of oxygen, this is the ratio of ^{18}O to ^{16}O relative to the ratio in an internationally accepted standard (Vienna Standard Mean Ocean Water or V-SMOW) on a parts per thousand (per mil) basis as shown in the following equation.

$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{V-SMOW}}{(^{18}O/^{16}O)_{V-SMOW}} \times 1{,}000$$

The oxygen isotope composition of the water samples was determined using a modification of the carbon dioxide equilibration method of Epstein and Mayeda[112]. The stable hydrogen isotopic composition (expressed as delta deuterium or δD and delta O-18 or $\delta^{18}O$) was determined by analyzing hydrogen quantitatively extracted from water[113]. Deuterium results are also reported relative to V-SMOW in the per mil notation. The standard deviations of the results of analysis for oxygen and hydrogen isotopic compositions are 0.08 and 0.9 per mil, respectively. The oxygen and hydrogen isotopic compositions were determined by the Department of Geosciences, University of Arizona, Tucson.

The analysis of stable isotopes in a water sample will result in negative values if the sample has less D or ^{18}O than standard ocean water. This is the case for all the sample results presented in this report. Isotope results are plotted on an x-y graph where $\delta^{18}O$ is the x-axis and δD is the y-axis. Points representing most precipitation samples worldwide plot on or close to the meteoric water line which is defined by the equation $\delta D = 8.0 \times \delta^{18}O + 10$.

When water evaporates, the liquid remaining becomes progressively “heavier” or enriched in heavy isotopes (D and ^{18}O). That is, the δD and $\delta^{18}O$ values both become progressively less negative. Because the water molecules containing ^{18}O are heavier than those containing D, during evaporation they diffuse to the atmosphere more slowly than water molecules containing D. Therefore, there is an increase in

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[111] See footnote 30.

[112] Epstein, S. and T. Mayeda. 1953. Variation of O18 content of waters from natural sources. Geochemica et Cosmochemica Acta 4(5): 213-224.

[113] Kendall, C. and T.B. Coplen. 1985. Multisample conversion of water to hydrogen by zinc for stable isotope determination. Analytical Chemistry 57: 1437-1440.

^{18}O relative to D and the isotopic composition plots on a line with a lower slope than the meteoric water line described above. In other words, evaporation causes the stable isotope results to plot along a line trending upward and to the right, but at a lower slope than the meteoric water line. The evaporative effect on the isotope composition is well documented in the literature, and these evaporative trend lines typically have slopes that range from 3 to 6 for the $\delta D/\ \delta^{18}O$ equation[114].

Groundwater Quality Data

There is little available shallow groundwater quality data in the Delta. HydroFocus collected water quality data on four Delta islands; Twitchell Island, Wright-Elmwood Tract, Jersey Island, and Bouldin Island. Analytes included nitrogen species, dissolved organic carbon, methyl mercury and salinity.

Results

Non-Delta area

Distribution and Temporal Variability of Groundwater Nitrate Concentrations

For the non-Delta area east and south of the Delta (Figure 1), we focused on assessing factors and processes likely affecting groundwater nitrate concentrations. Within this section, we discuss the relationship of nitrate concentrations to groundwater recharge, soil texture, subsurface texture, land use, depth to groundwater, and depth of wells. The following sections describe the distribution of groundwater nitrate concentrations, other water quality data and the spatial variability in groundwater recharge, soil texture, subsurface texture, land use, and depth to groundwater.

Figures 6 through 14 show the distribution of average groundwater nitrate concentrations for wells throughout the Coalition Service Area from 1969 to 2013 in 5-year intervals. The spatial frequency of relatively high nitrate concentrations generally increased with time. However, the number of samples also increased with time (Figure 15). Concentrations were mostly below the MCL of 45 mg/L during 1969 – 1978 (Figures 6 and 7). During 1979 – 1983, nitrate concentrations above the MCL were measured in wells located within the south-central DPR vulnerability area surrounding Manteca and in the south-western Delta southeast and northwest of Tracy (Figure 8). Large numbers of samples were collected during this period relative to previous and subsequent years prior to 2000 (Figure 14). Mapped concentrations during 1984 – 1993 (Figures 9 and 10) were generally low relative to 1979 – 1983 (Figure 8). Figures 8 through 12 indicate generally increasing nitrate concentrations in the area surrounding Manteca and northward extending to and surrounding Lodi.

From 2009 – 2013, wells in agricultural areas with average nitrate concentrations at or above the MCL are located primarily in the northern (near Lodi) and southwestern (near Manteca) part of the Service Area, southern Delta and southwest of the Delta near Tracy (Figure 14). The areas where there are groundwater nitrate concentrations above the MCL in the southeastern part of the Coalition Service Area surrounding Manteca generally correspond to the DPR GWPA.

[114] Gat, J.R. and Gonfiantini (Eds.). 1981. Stable isotope hydrology-Deuterium and oxygen-18 in the water cycle, Tech. Rep. Ser. International Atomic Energy Agency, 210.

Northeast of Stockton, southeast of Lodi and southeast of Tracy, localized high groundwater nitrate concentrations lie outside of the DPR GWPA. Nowhere within the Coalition Service Area do areas of high nitrate concentrations coincide with State Water Board HVAs (Figure 14).

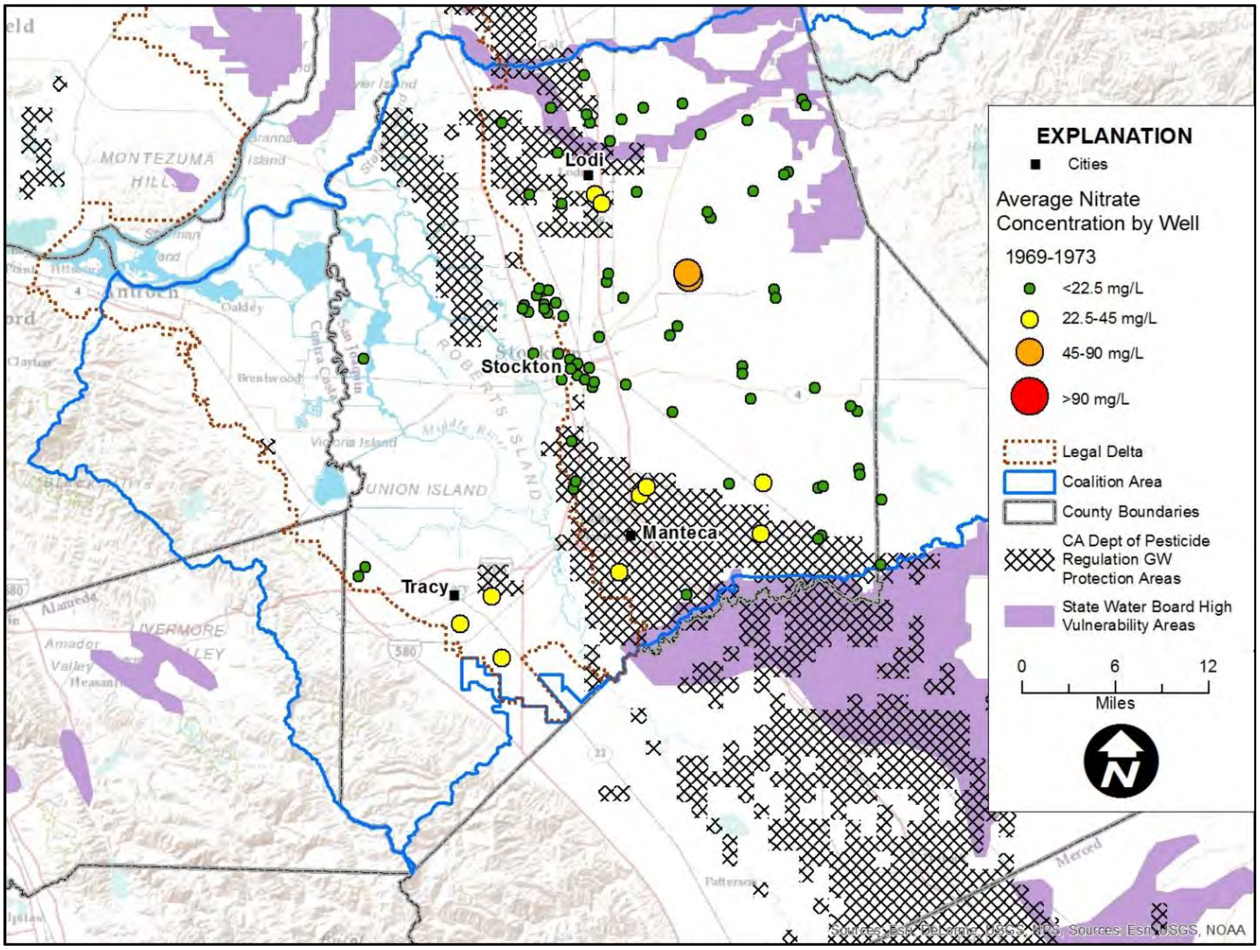

Figure 6. Distribution of average nitrate concentrations, 1969 to 1973.

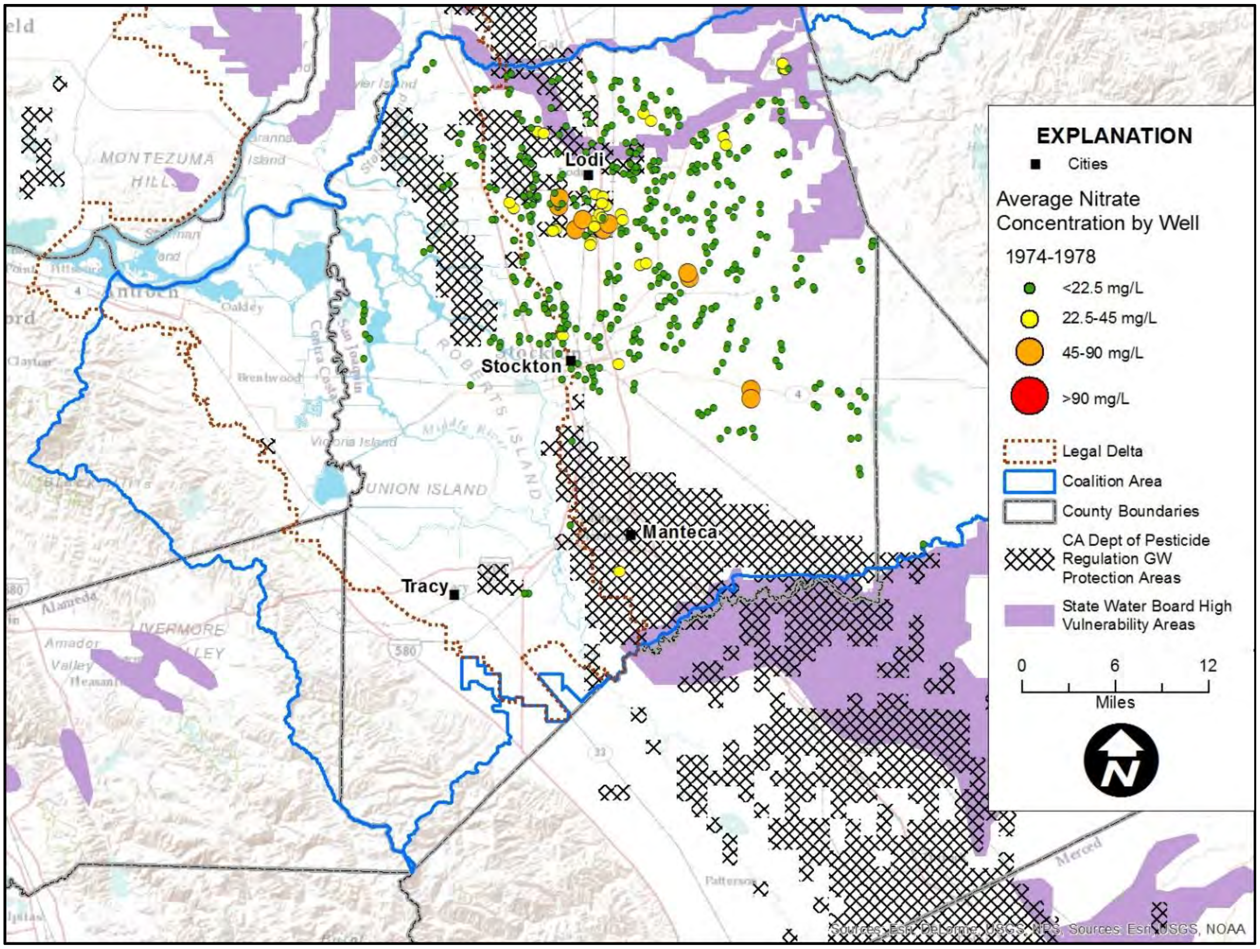

Figure 7. Distribution of average nitrate concentrations, 1974 to 1978.

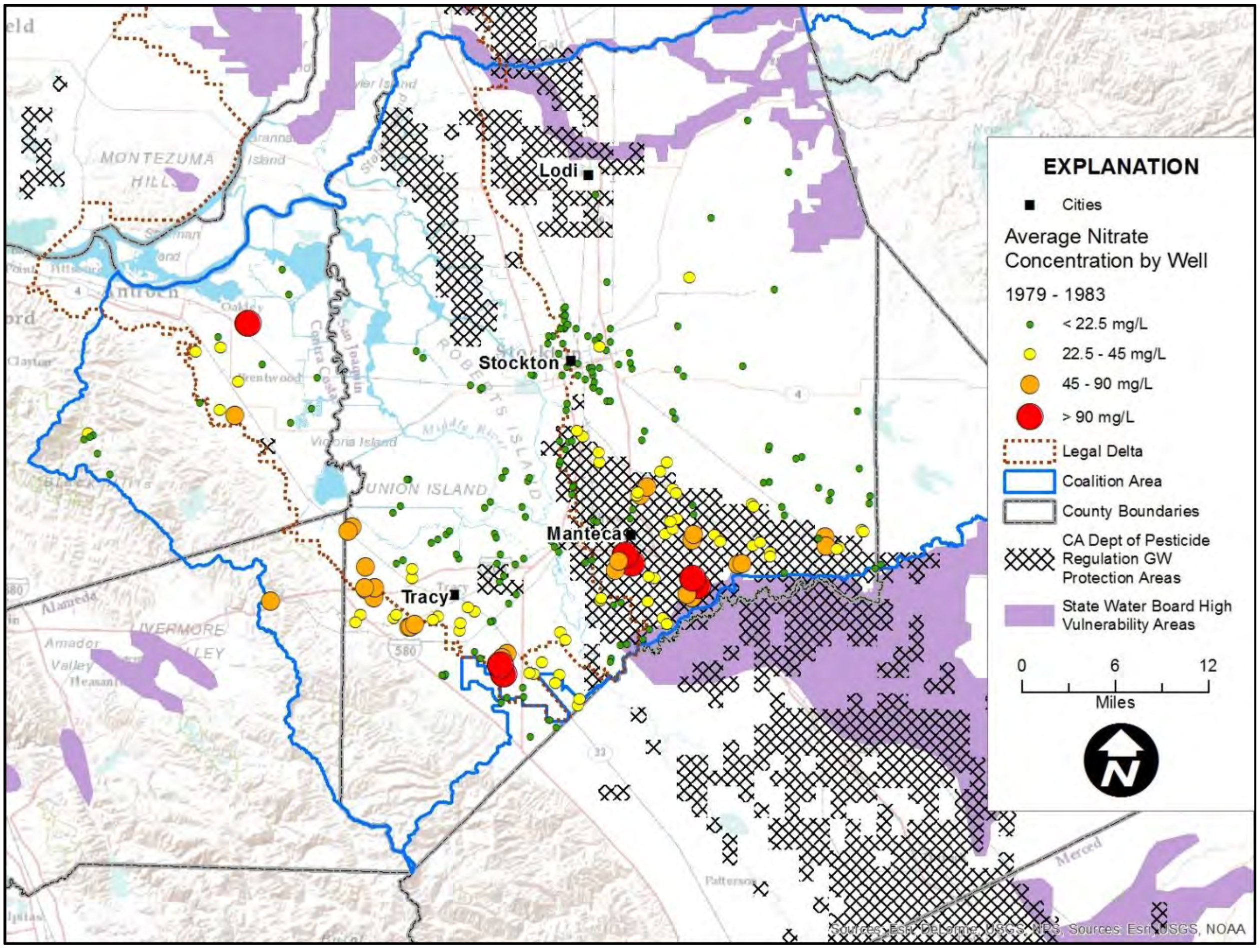

Figure 8. Distribution of average nitrate concentrations, 1979 to 1983.

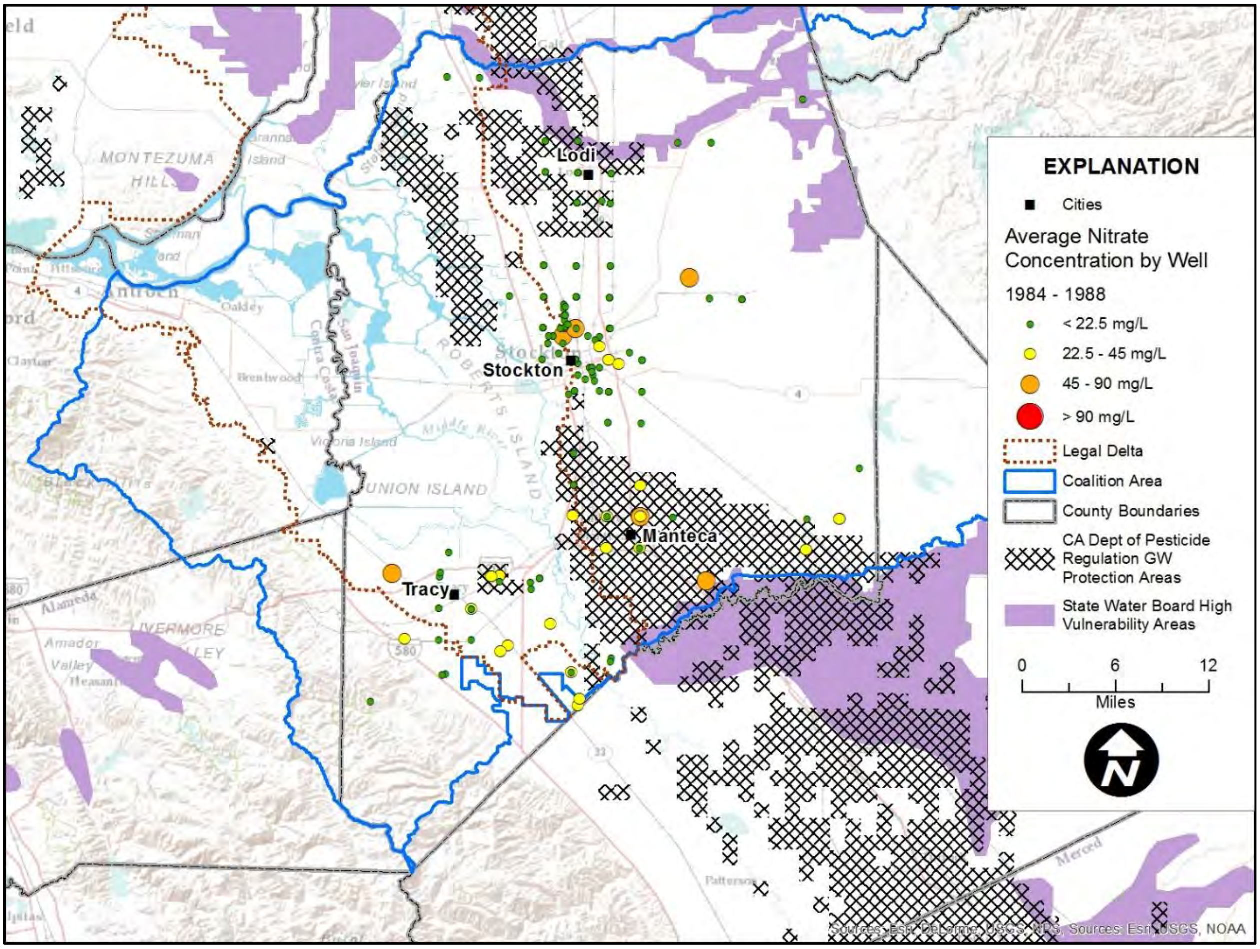

Figure 9. Distribution of average nitrate concentrations, 1984 to 1988.

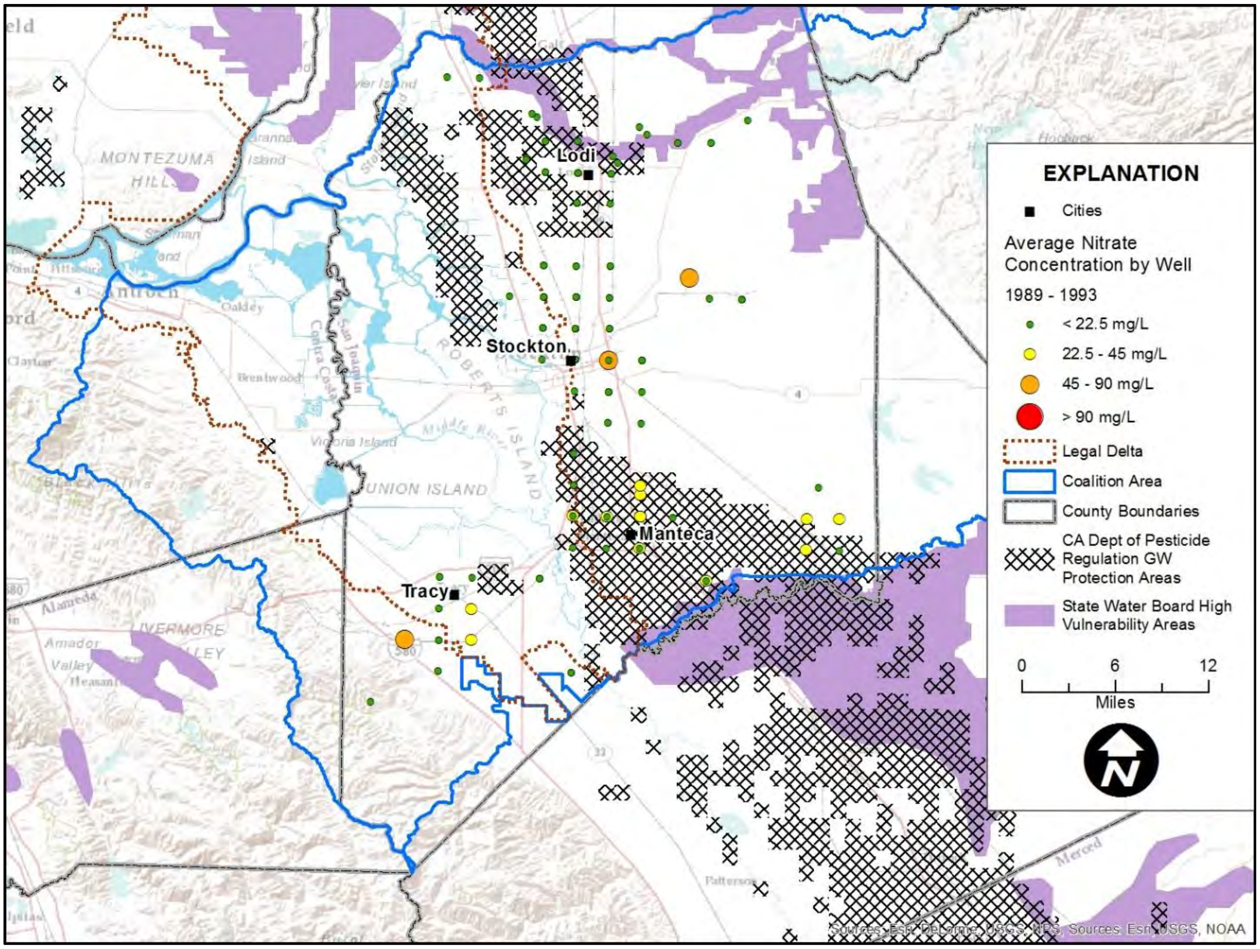

Figure 10. Distribution of average nitrate concentrations, 1989 to 1993.

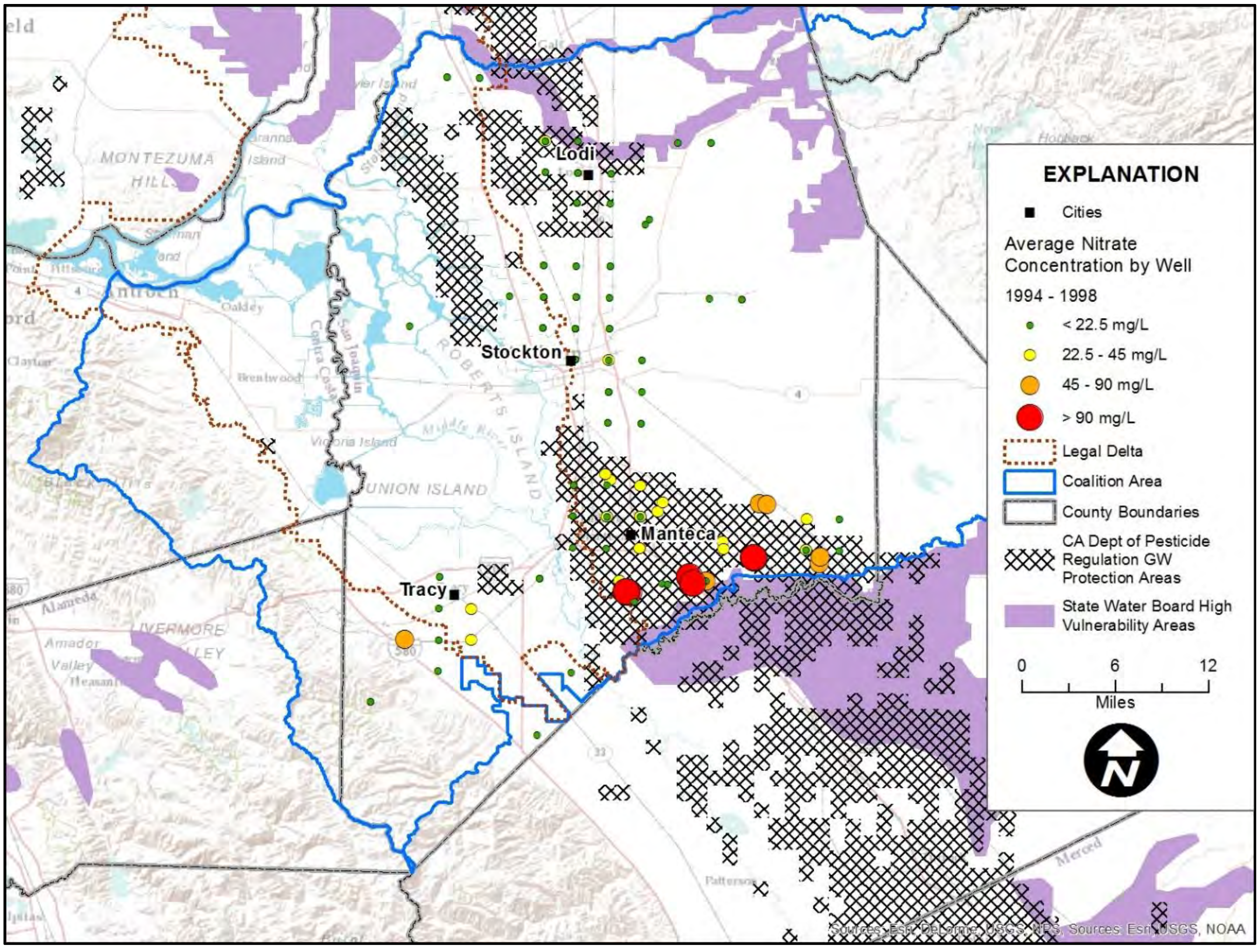

Figure 11. Distribution of average nitrate concentrations, 1994 to 1998.

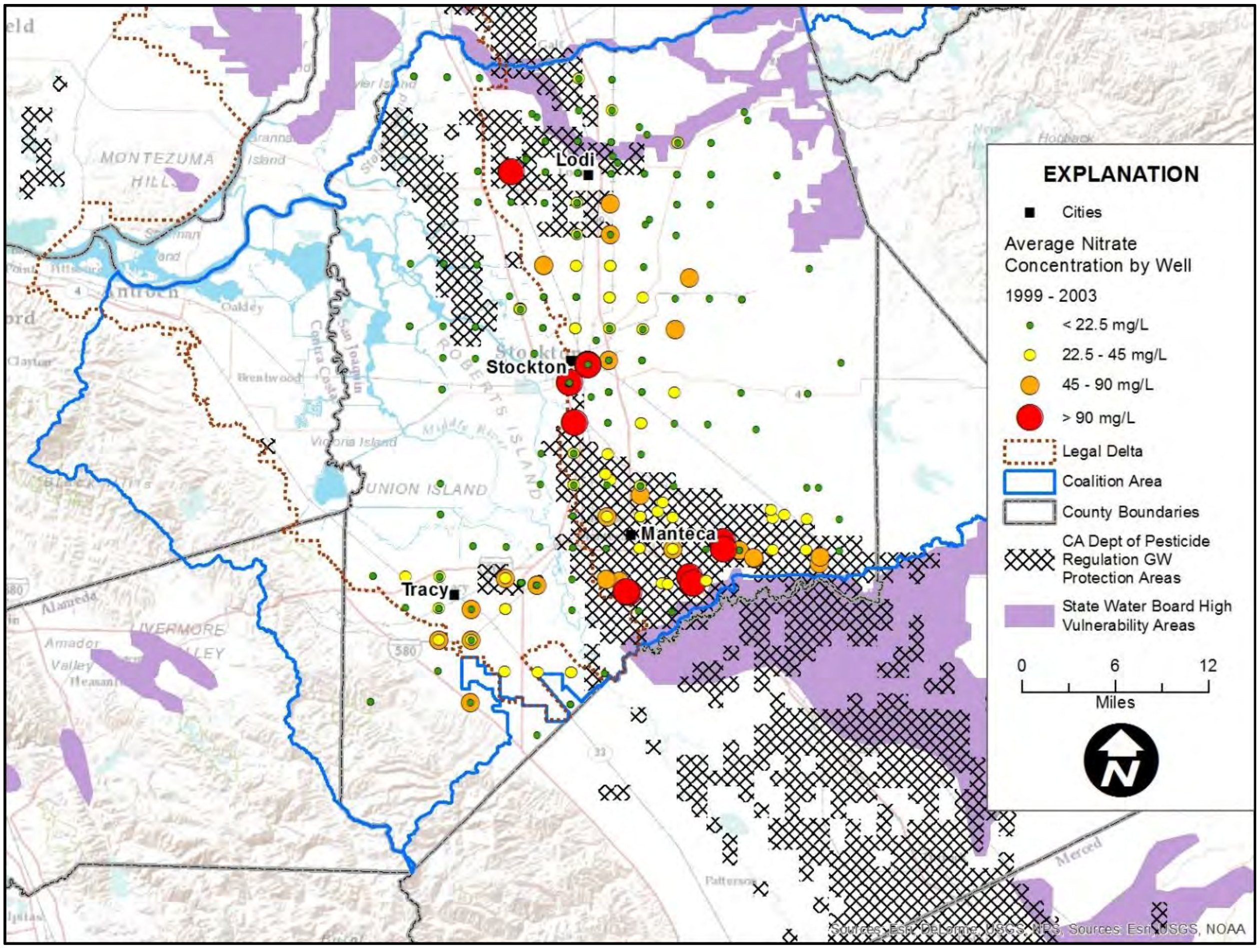

Figure 12. Distribution of average nitrate concentrations, 1999 to 2003.

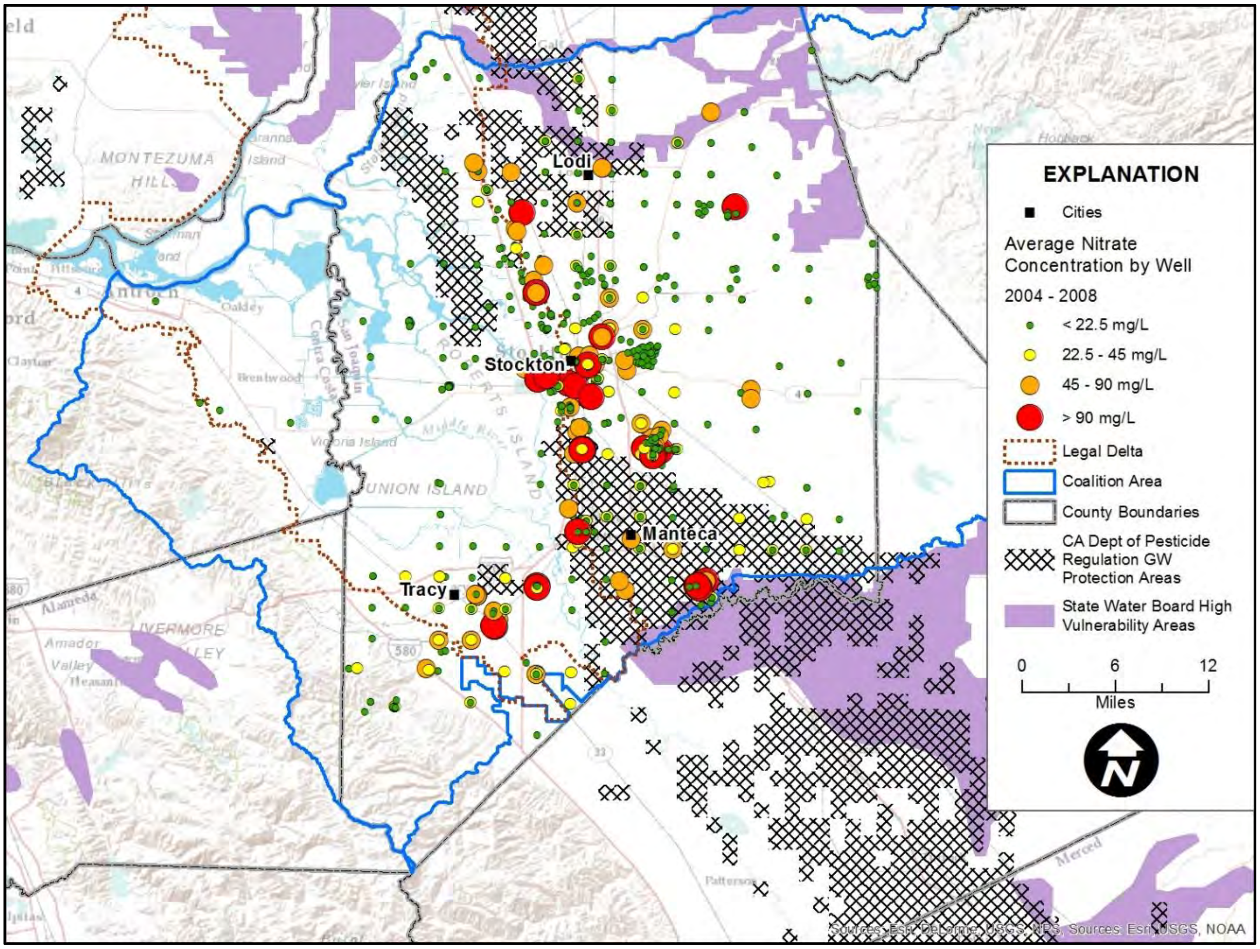

Figure 13. Distribution of average nitrate concentrations, 2004 to 2008.

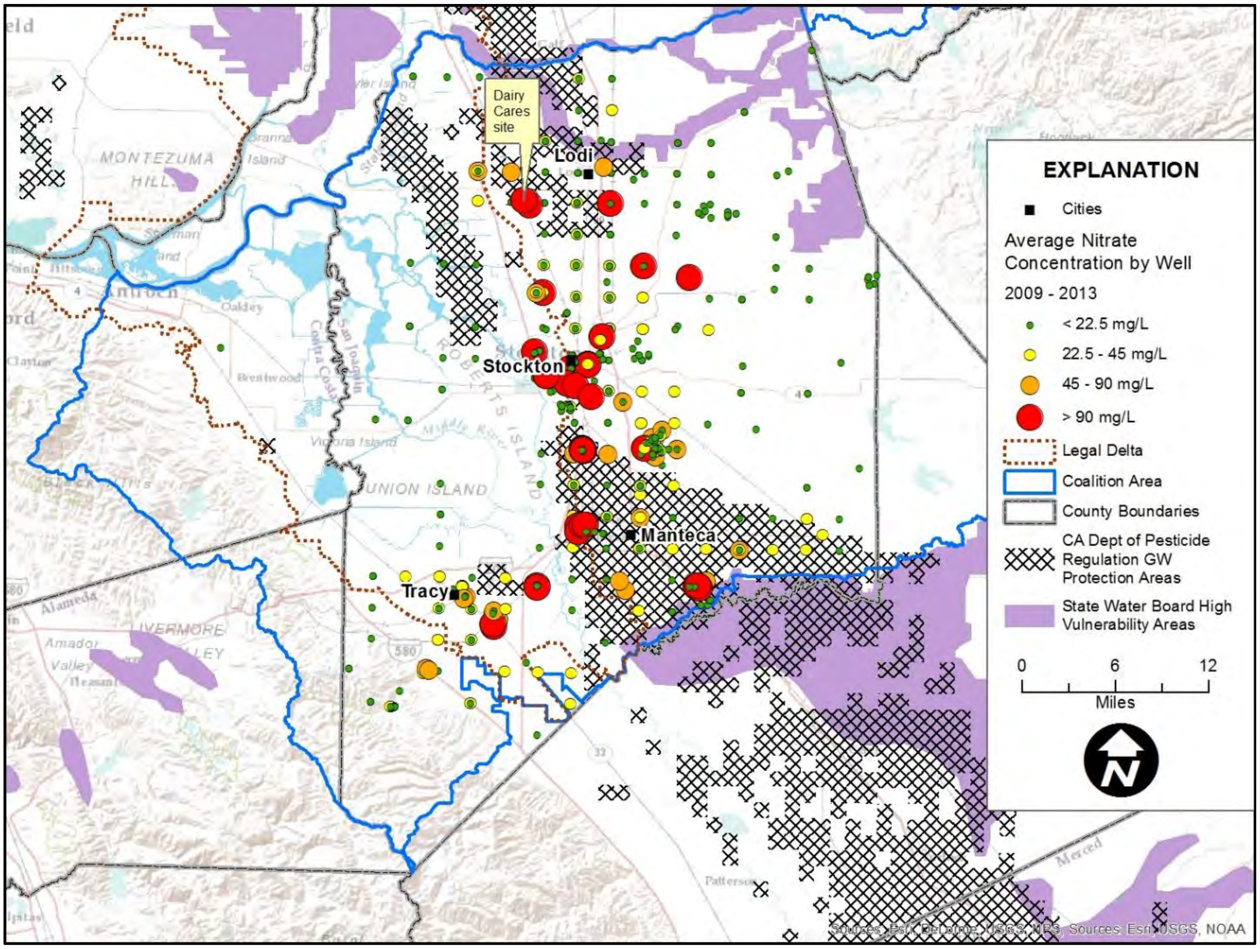

Figure 14. Distribution of average nitrate concentrations, 2009 to 2013.

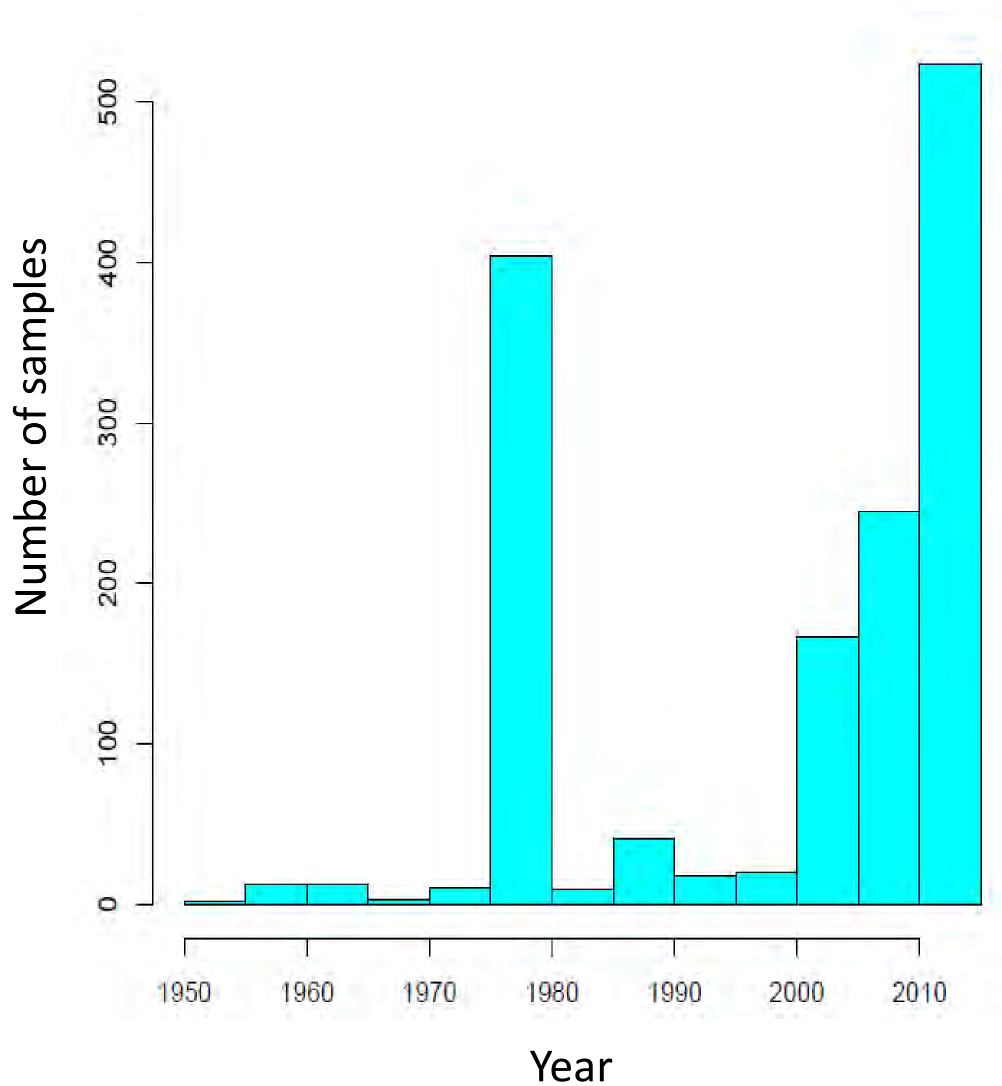

Figure 15. Number of samples analyzed for nitrate in five year intervals in the non-Delta portion of the Coalition Service Area.

We examined 28 wells with sufficient history of nitrate concentrations to determine the statistical significance of trends. Nine wells showed significant increasing trends, three wells showed significant decreasing trends and 16 wells did not show a significant trend. Figure A3 in the Appendix shows the well locations with their trends and the associated graphs show the nitrate concentrations over time for the 28 wells.

Relation of nitrate concentrations to groundwater major-ion chemistry

Trilinear diagrams (Figure 16) are a useful way to characterize and display groundwater chemical data. Major cations (calcium, magnesium, sodium and potassium) and major ions (chloride, sulfate and bicarbonate) are plotted on a charge-equivalent basis[115]. Cations are plotted on the lower left triangle, anions on the lower right triangle, and the central diamond integrates the data. Izbicki and others[116] identified three groups having different chemical compositions within the Coalition Service Area. The Group 1 delineation represents most of the wells sampled by the USGS as described in Izbicki and others and represents shallow wells and wells screened in shallow and deeper zones. The Group 2 delineation represents deep groundwater samples. All the samples in Group 3 had chloride concentrations greater than 100 mg/L.

Group 1 and Group 3 delineations contained points with nitrate concentrations ranging from 22.5 to over 45 mg/L (green and red points). The samples in Group 3 were collected in the eastern part the Coalition's non-Delta Service Area and likely represent groundwater influenced by groundwater from marine sediments close to the San Joaquin River. Nitrate concentrations were universally less than 22.5 mg/L in samples whose points plotted within the Group 2 delineation which represented deep wells in Izbicki and others[117]. The distribution of nitrate concentrations in Figure 16 is generally consistent with Boyle and others[118]; lower nitrate concentrations are associated with points that represent samples that plot in the sodium/potassium-bicarbonate/carbonate (Na/K – HCO3/CO3) area of the central diamond (see Figure 17 for delineation of water types). They hypothesized that geochemical evolution that results in dissolution and carbonate minerals and exchange of calcium and magnesium for sodium on clays occurs as groundwater moves along its flow path. Consistently, Izbicki and others' deeper groundwater samples plotted in this area of the diamond. Also, as discussed below, deeper wells had lower nitrate concentrations.

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[115] Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254

[116] John A. Izbicki, Loren F. Metzger, Kelly R. McPherson, Rhett R. Everett, and George L. Bennett V, 2006, Sources of High-Chloride Water to Wells, Eastern San Joaquin Ground-Water Sub-basin, California, US Geological Survey Open File Report 2006-1309.

[117] ibid

[118] Dylan Boyle, Aaron King, Giorgos Kourakos, Katherine Lockhart, Megan Mayzelle, Graham E. Fogg and Thomas Harter, 2012, Technical Report 4, Addressing Nitrate in California's Drinking Water, With a Focus on Tulare Lake Basin and Salinas Valley Groundwater, Report for the State Water Resources Control Board Report to the Legislature.

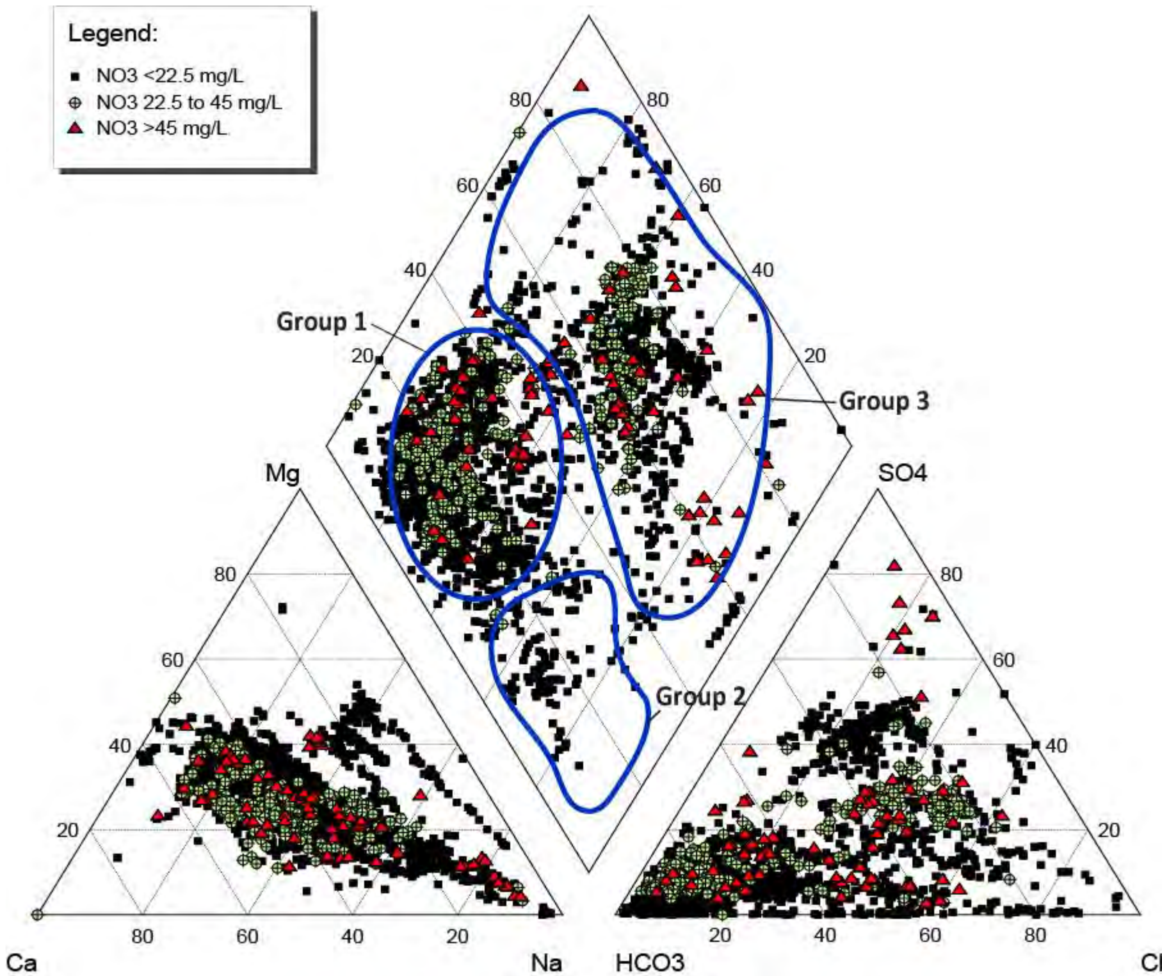

Figure 16. Chemical characteristics of samples by nitrate concentration. Groups delineated by Izbicki et al 2006[119].

[119] See footnote 117.

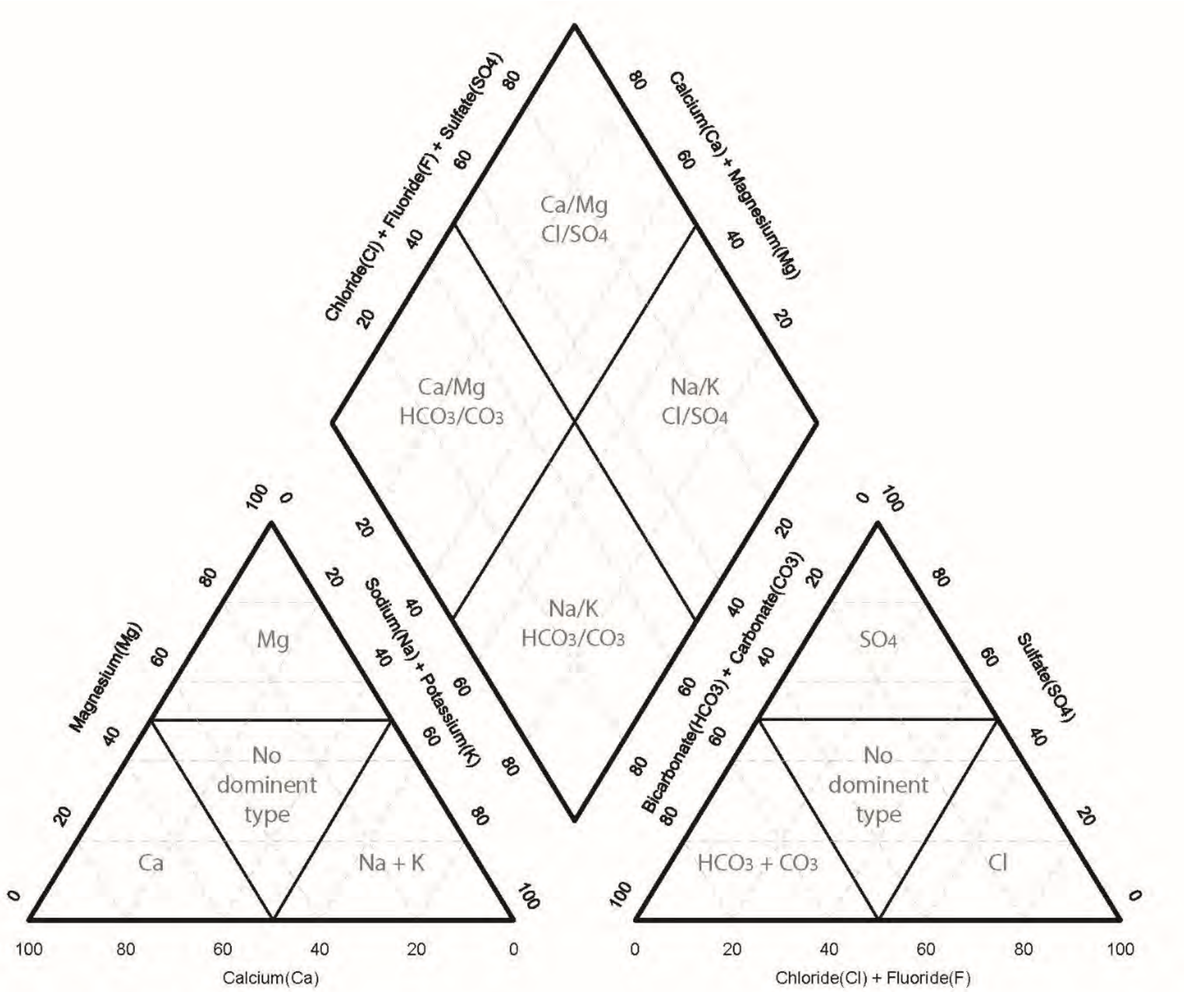

Figure 17. Chemical characteristics and areas of ionic dominance represented by the Trilinear diagram.

Nitrate concentrations, groundwater levels, well depths, and depth to groundwater

We obtained well depth information for 399 wells within agricultural areas. Depths ranged from 44 to 775 feet below land surface and the average depth was 205 feet. Most wells having nitrate data were shallower than 400 feet. For all nitrate data, concentrations above the MCL were associated with wells shallower than 250 feet (Figure 18).

Figure 19 shows the distribution of the average depth to groundwater and nitrate concentrations in the Coalition Service Area for 2009 - 2013 which is the most recently available. Groundwater depths generally range from 200 feet in the northeastern part of the Coalition Service Area to less than 20 feet near the Delta. Nitrate concentrations ranging from within 50% of, to over the MCL were predominantly associated with areas where groundwater levels are within 130 feet of land surface.

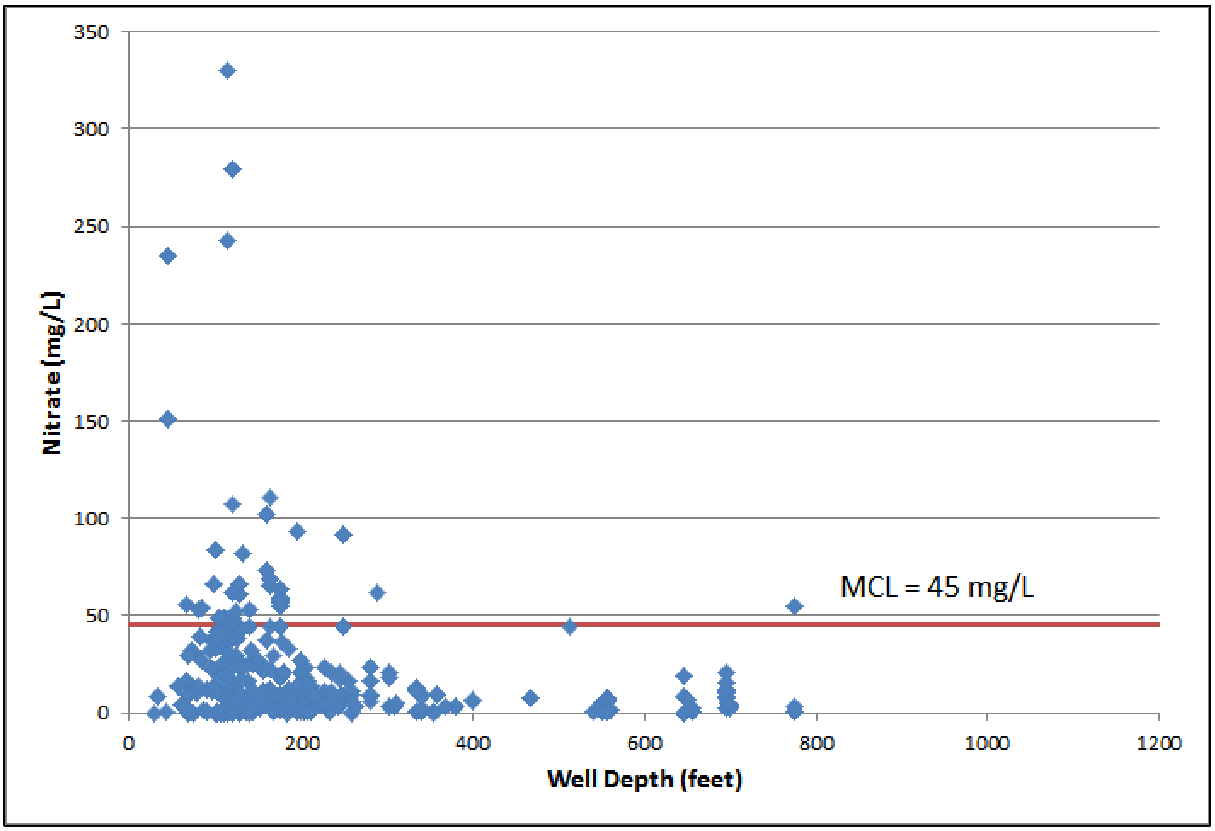

Figure 18. Relation of nitrate concentrations in wells and well depth for all data within agricultural areas.

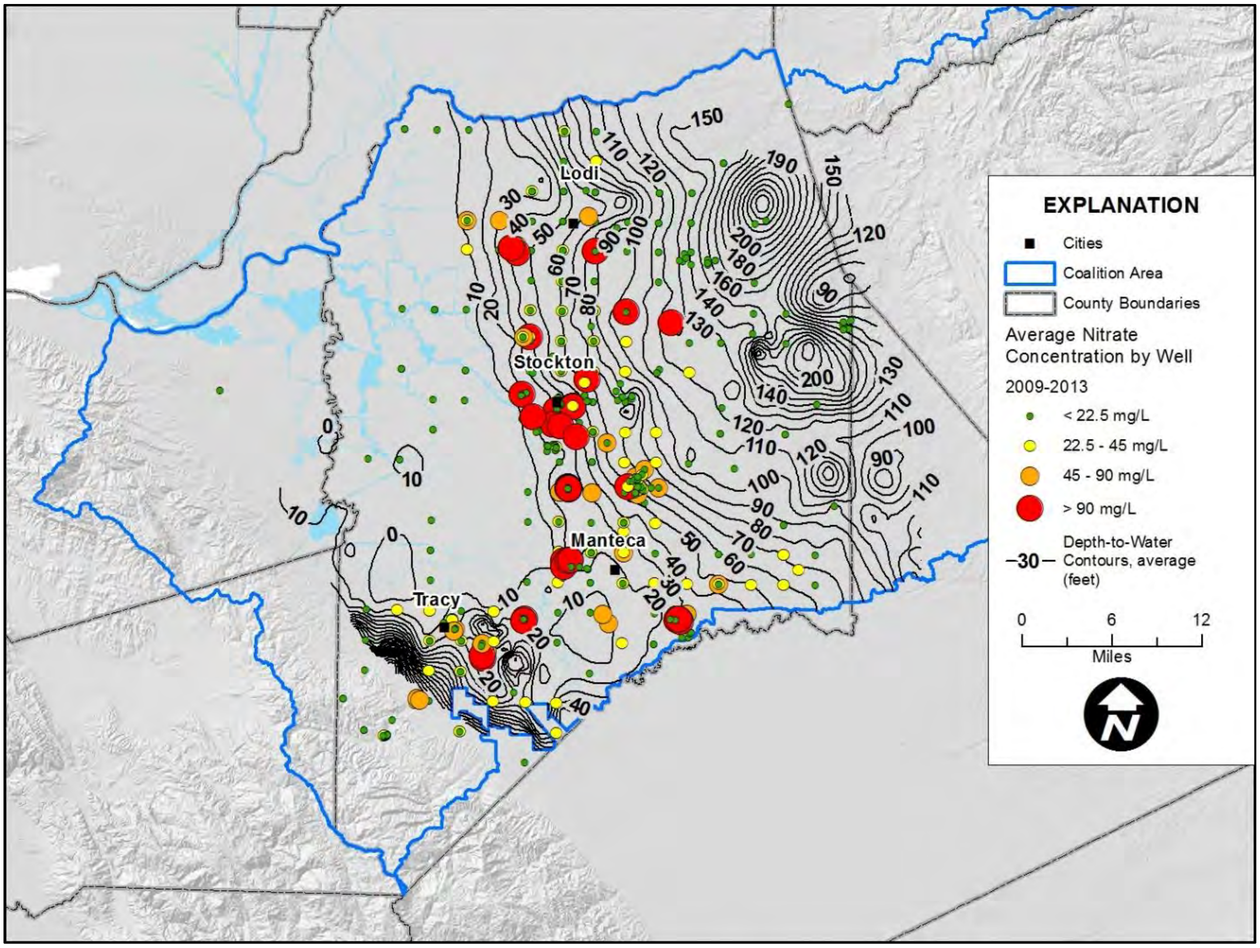

Figure 19. Distribution of average depth to groundwater and average 2009-2013 groundwater nitrate concentrations.

Using data provided by San Joaquin County, we created hydrographs from selected wells shown in Figure A1 in the Appendix. Most wells had decreasing water level trends; however five wells had stable to increasing water level trends. These wells are located south of Stockton, southwest of Manteca and near the boundary of San Joaquin and Stanislaus counties.

Relation of nitrate concentrations and other constituents

Nitrate concentrations were positively and significantly correlated with salinity (total dissolved solids, conductivity) and salinity-related variables. These included (correlation coefficients are in parentheses) conductivity (0.42), hardness (0.93), total dissolved solids (0.64), calcium (0.69), magnesium (0.66), sodium (0.43), chloride (0.50) and sulfate (0.60). Since groundwater salinity generally increases with increasing proximity to the San Joaquin River where groundwater levels are shallowest, the higher nitrate concentrations are likely the result of the shallow water levels which are spatially associated with the higher salinities.[120] Where data was available, we did not find any relation between oxidation-

[120] See footnote 117.

reduction potential, dissolved oxygen, or pH. We have used the distribution of nitrate concentrations to delineate high and low vulnerability areas within the Coalition Service Area.
We examined 10 wells with sufficient history of total dissolved solids (TDS) concentrations to assess statistically significant trends. Five wells showed significant increasing trends, two wells showed a significant decreasing trend, and three wells did not show a significant trend. Figure A4 in the Appendix shows the well locations with their trends and the following graphs in the Appendix show TDS concentrations over time from the ten wells.

Land use and Nitrate Concentrations

Figure 20 shows land use based on the CDWR 1996 land use survey for the non-Delta area and the 2007 land use survey in the Delta. A substantial portion non-Delta Coalition Service Area is native vegetation near the eastern boundary. Deciduous fruit and nut crops and vineyards occupy a large portion of the central eastern part of the non-Delta Coalition Service Area. Field, grain, and hay crops tend to dominate in the Delta.

In addition to the CDWR land use surveys, we obtained land use maps developed by the USDA using satellite data. In the non-Delta area, the land use maps for 1996 (CDWR) and 2012 (USDA) were not substantially different. Key differences included a replacement of: truck crops by field crops, hay and grain, deciduous fruits and nuts and pasture (44,400 acres); pasture and vineyards by deciduous fruits and nuts (21,800 acres); pasture and native lands with vineyards (12,715 acres); and conversion of agricultural land to urban areas (24,300 acres).

Of the irrigated agricultural lands within Coalition Service Area boundaries, the most prevalent crop classes based on CDWR land use surveys are pasture (12.7%), field crops (13.5%), deciduous fruits and nuts (18.4%), vineyards (12.3%), and truck crops (6.6%).

The number of wells within each land use category varied from none for citrus and subtropical to 501 for urban (Figure 21). Figure 21 also shows the relation of groundwater nitrate concentrations and 1996 (San Joaquin County), 2004 (Stanislaus), and 2007 (legal Delta) land use categories. The preponderance of nitrate concentrations above the MCL south and southeast of Manteca is associated with fruits and nuts and field crops. Concentrations within 50% of and above the MCL in the Lodi area are associated primarily with vineyards. North of Stockton, mapped concentrations ranging from half of the MCL to over 90 mg/L are associated with primarily with deciduous fruits and nuts.

Statistical analysis using methods described in the Methods Section indicate a general lack of significant differences for groundwater nitrate concentrations by land use in agricultural areas (Figure 22). Figure 22 shows the similarity in median nitrate values for all agricultural land uses. However, our analysis indicated that groundwater nitrate concentrations associated with deciduous fruits and nuts were significantly greater than nitrate concentrations associated with truck and field crops, idle agricultural lands, pastures, and vineyard at the 95% confidence level.

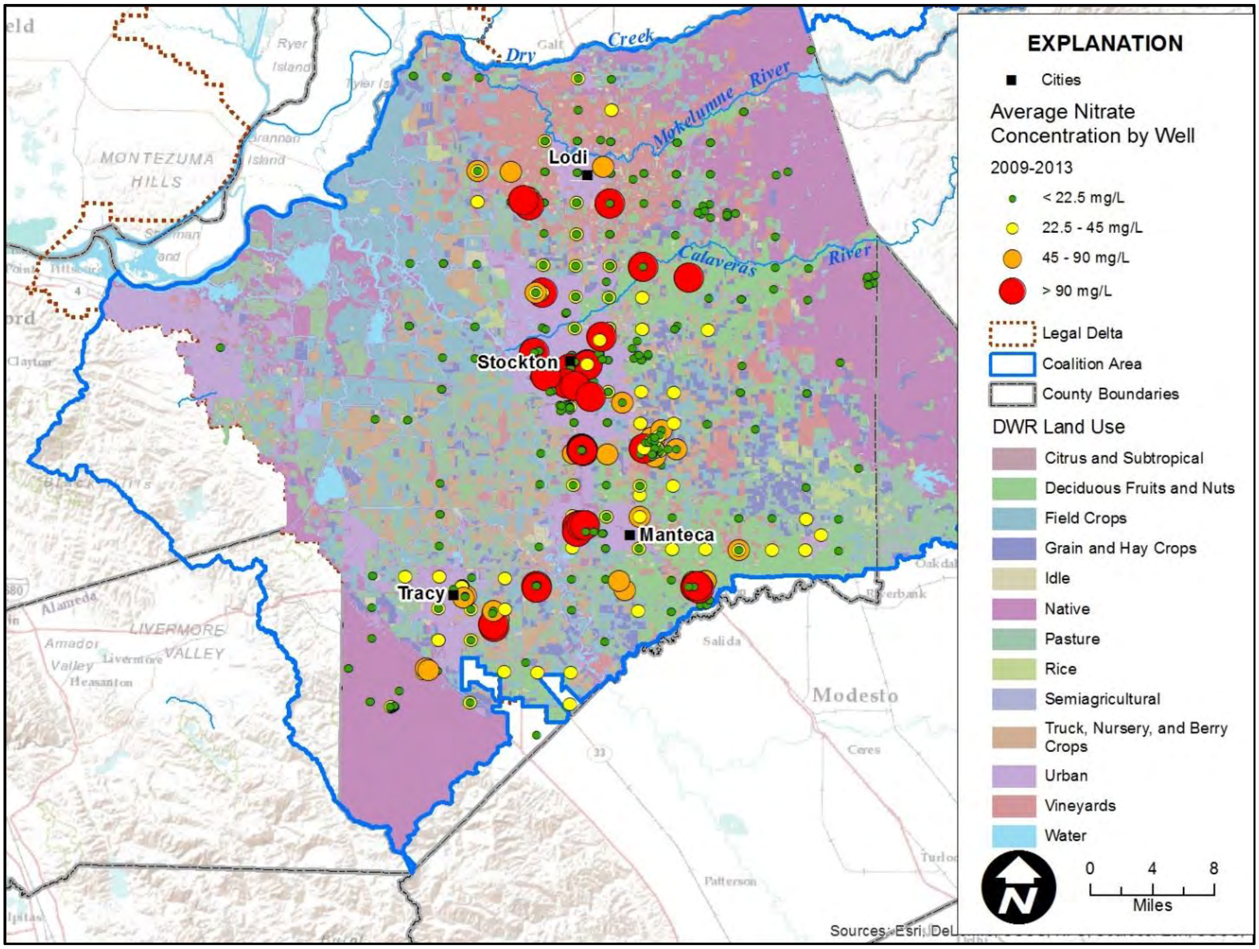

Figure 20. 1996 CDWR land use for San Joaquin County, 2004 CDWR land use for Stanislaus County, and average groundwater nitrate concentrations for 2009-2013.

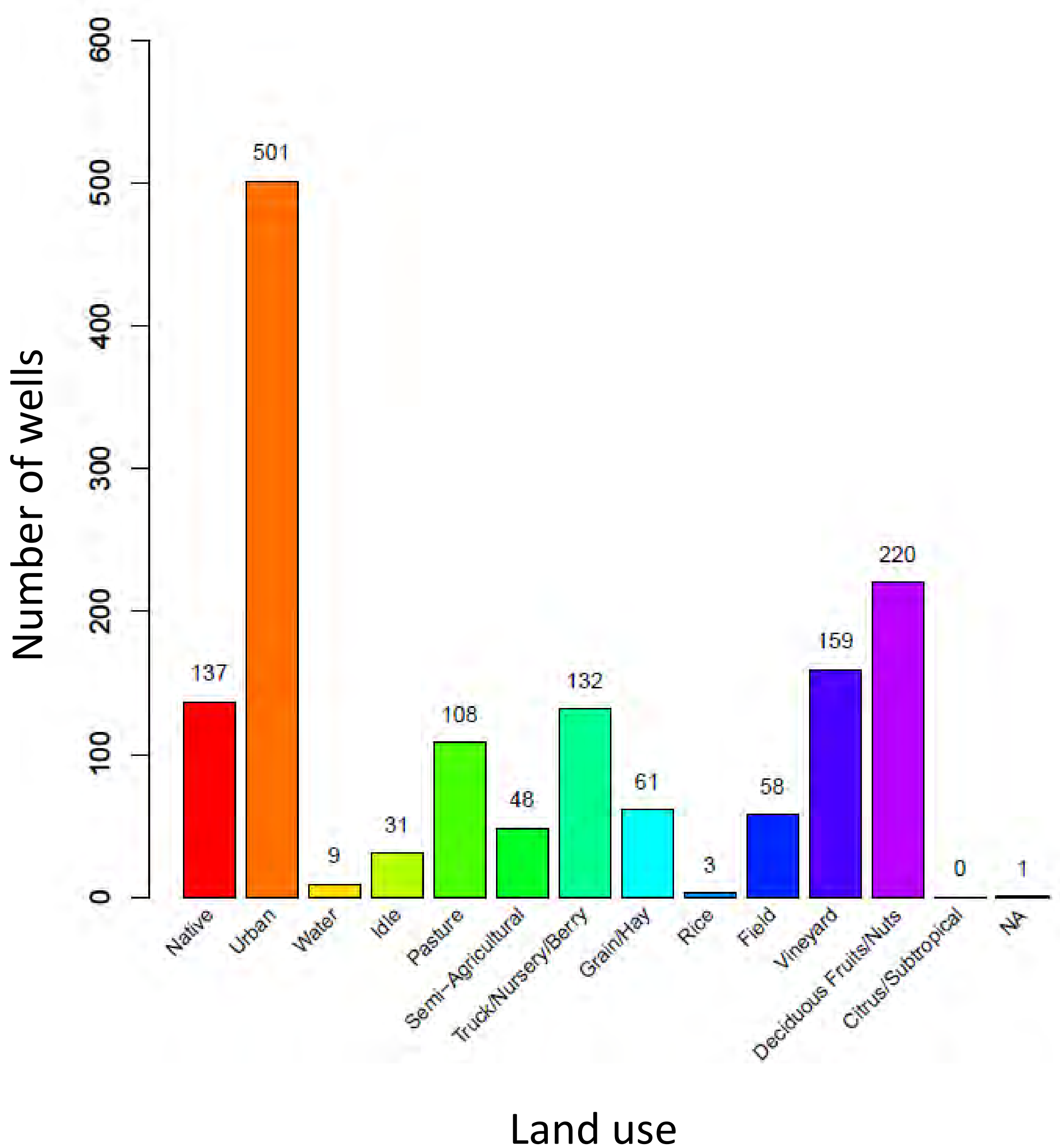

Figure 21. Number of wells by 1996 land use category.

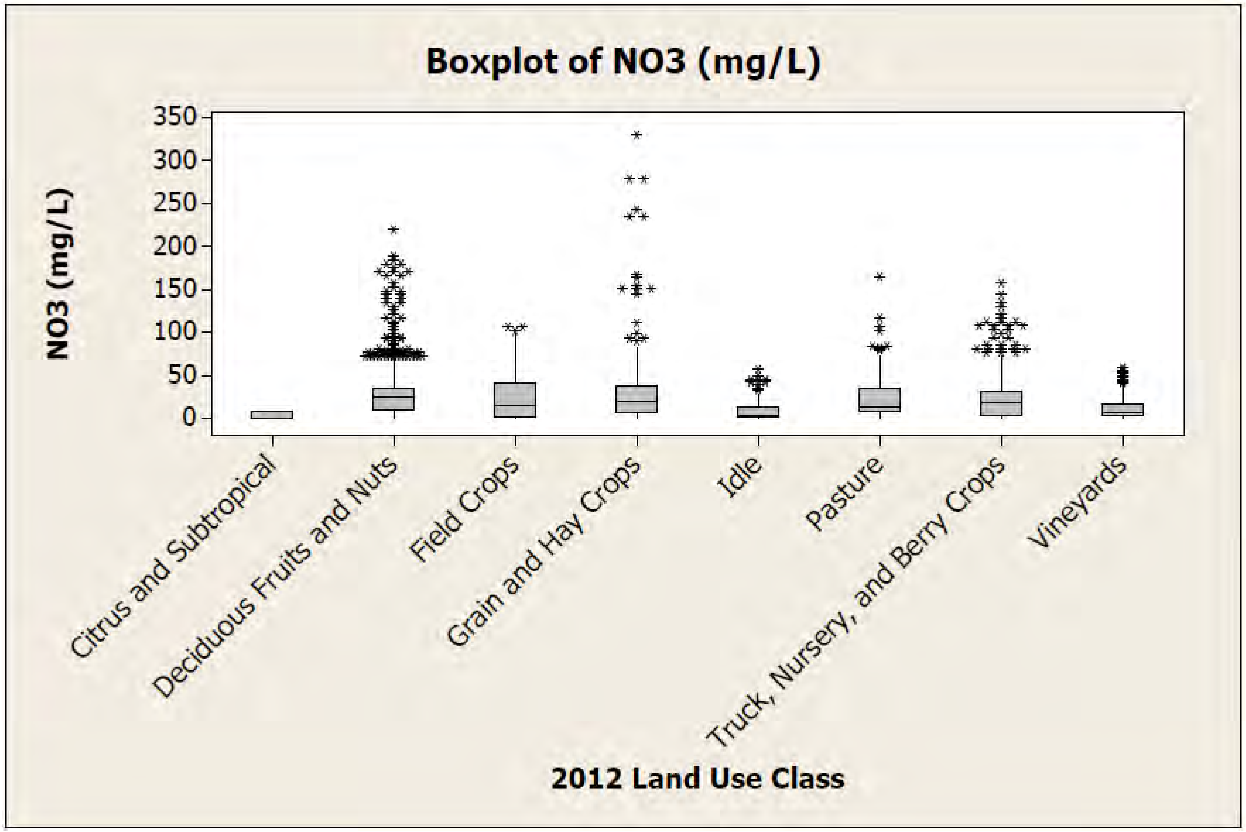

Figure 22. Box plots for nitrate concentrations for 2012 agricultural land uses. Shaded rectangles represent 75% of the data. Horizontal lines in the rectangles represent the median. Vertical lines extending from the rectangle represent 90% of the data. Asterisks indicate outliers which lie beyond 90% of the data.

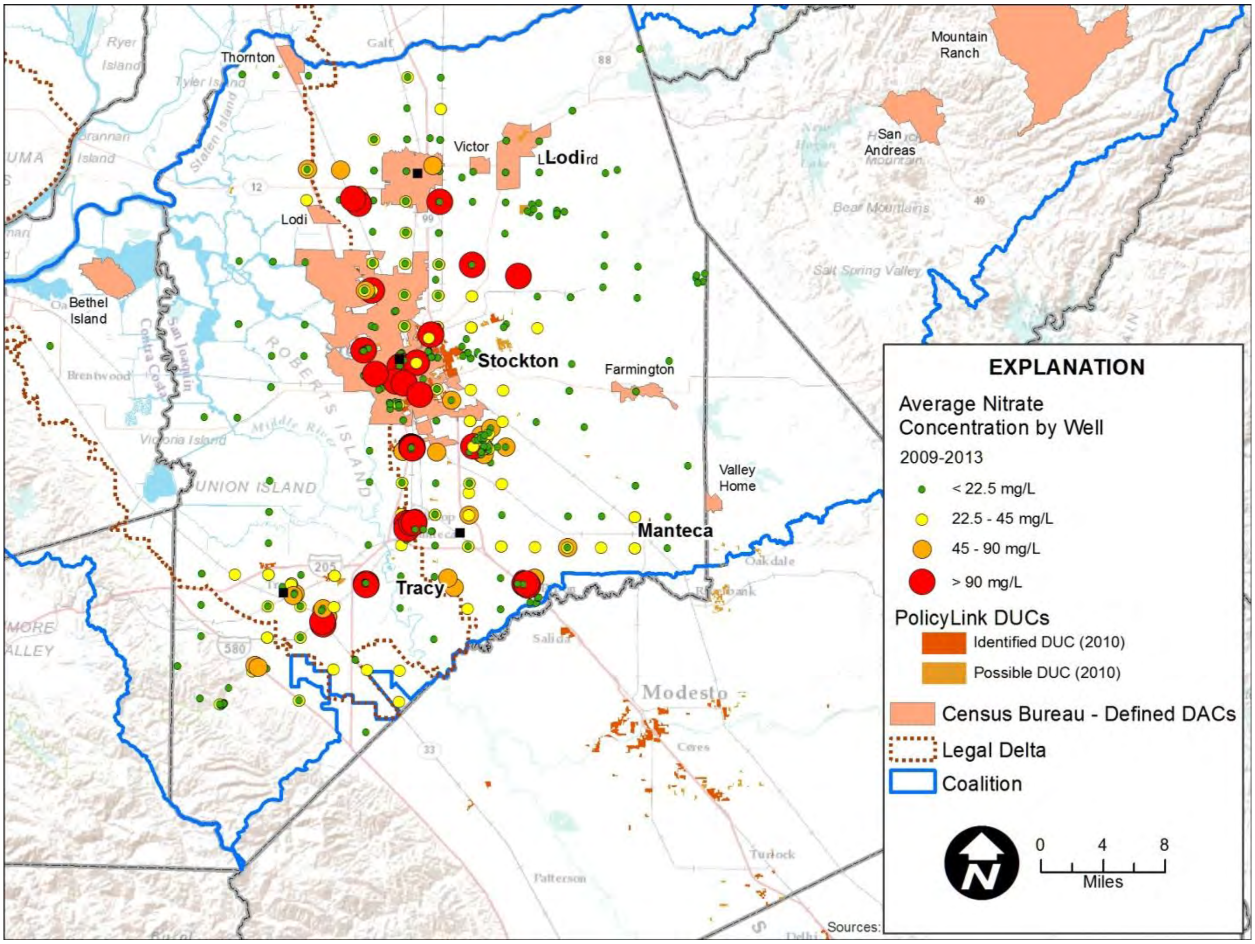

Figure 23. Disadvantaged communities and average groundwater nitrate concentrations for 2009-2013.

Average 2009-13 nitrate concentrations are shown with disadvantaged communities (DACs) and disadvantaged unincorporated communities (DUCS) in Figure 23.

Soil and Subsurface Lithology

Figure 24 shows the distribution of soil texture within the Coalition Service Area based in the NRCS Soil Survey[121]. Sandy soils include sandy loam, sandy clay loam, sandy loam, loamy sand and sand (Figure 5). Loamy soils include clay loams and loams. The clayey delineation includes clay and silty clay. Within the non-Delta area, sandy and loamy soils predominate throughout the central eastern, northern and southern areas of the Coalition Service Area. There are large areas of clayey soils in the central and southeastern parts of the Coalition Service Area north and northeast and south and southeast of Stockton. The eastern part of the non-Delta Coalition Service Area contains intermixed loamy, clayey, sandy and silty soils. In Stanislaus County, silt-textured soils (silty clay loams, silty loams and silt) predominate.

[121] http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

In the Delta, true surface organic soils or highly organic mineral soils or histosols predominate in the central, eastern and southern Delta (Figure 24). These are predominantly medisaprists and include the Rindge, Kingile, Webile, Shinkee, and Shima soil series[122]. A small portion of less decomposed medihemist histosols is present in the central Delta (Figure 24).

We plotted nitrate concentrations on the soils map (Figure 24). The highest average (2009 – 2013) nitrate concentrations (over the MCL and above 90 mg/L) southeast of Lodi, south of Stockton and south and southeast of Manteca are generally associated with sandy soils. Concentrations above 90 mg/L are associated with loamy soils in the area northeast of Stockton.

Maps showing the distribution of soil pH and salinity are shown in figures A4-1 and A4-2 in the Appendix and do not appear to bear spatial relationship to groundwater nitrate concentrations. In general, lower pH soils with pH values below 6 were mapped in the eastern areas of the Coalition Service Area in the Delta. Alkaline soils with pH values greater than 8 occur at the eastern edge of the Delta south of the Delta. With the exception of small areas in the southern part of the Coalition Service Area, soil salinity values are less than 1 mmho/cm (less than 0.1 Siemen/m).

Figures 25 through 30 show the distribution of percent coarse-grained (sand and gravel) deposits in 50-ft intervals in the subsurface for the mile-square grid of the CVHM. These distributions were developed from the analysis of Well Completion Reports by the USGS from throughout the Coalition Service Area. We extracted the data from the model extending to 300-ft depth because this is the approximate depth of municipal water-supply wells in the Coalition Service Area. In the first 50 feet, darker areas representing over 40% coarse-grained deposits tend to predominate near the Stanislaus River and at the eastern edge of the Coalition Service Area near the foothills. There is also an area with greater coarse-grained percentages south of the Mokelumne River in the eastern part of the Coalition Service area. The pattern of relatively greater abundance of coarse-grained deposits in these areas is evident in the deeper depth intervals also (Figures 26 through 30). However, the percent coarse-grained deposits decreased with depth in in the south-central area of the Coalition Service Area adjacent to the Stanislaus River.

[122] McElhinney, M.A, 1992, Soil Survey of San Joaquin County, U.S. Department of Agriculture, Soil Conservation Service. Tugel, A.J, 1993, Soil Survey of Sacramento County, U.S. Department of Agriculture, Soil Conservation Service.

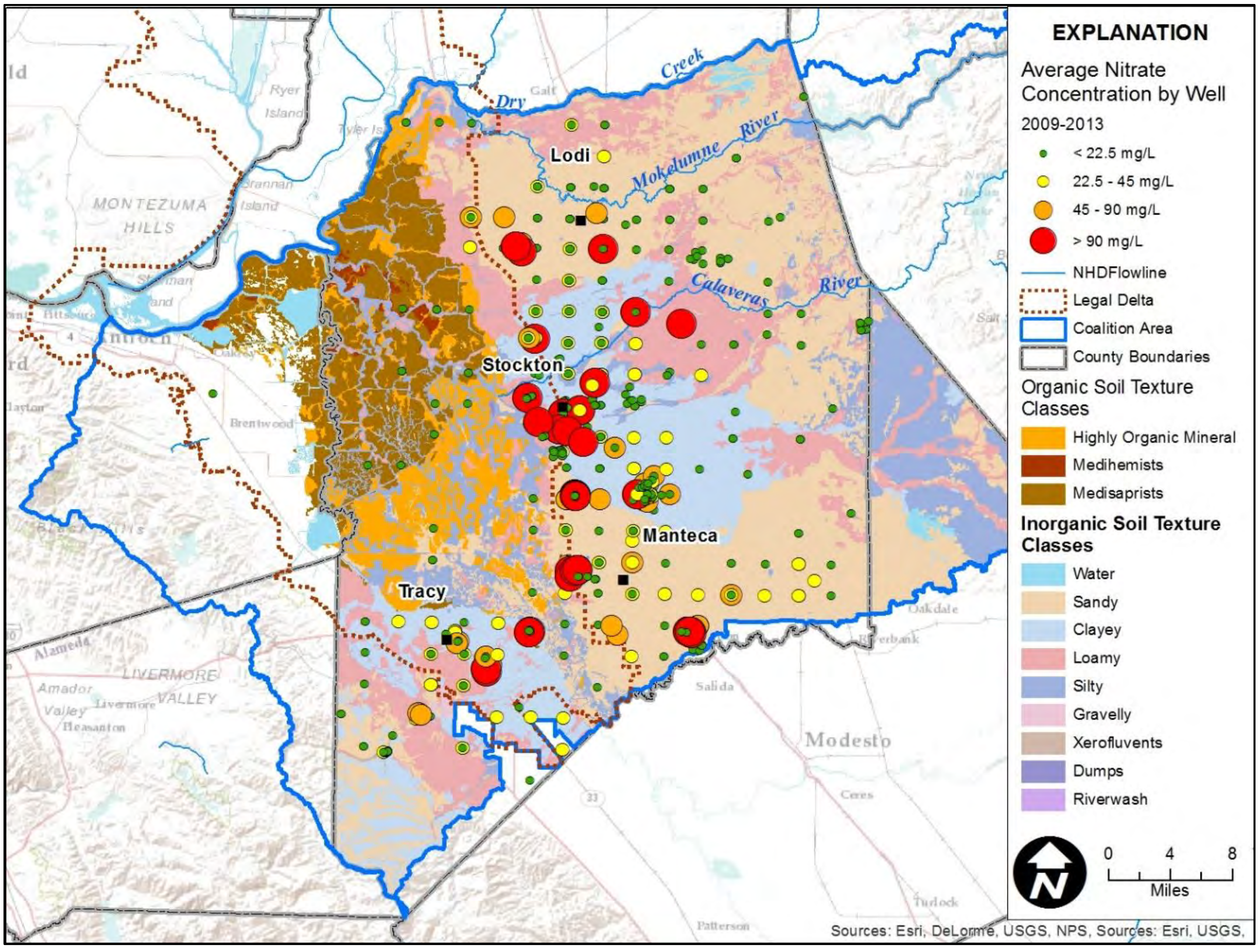

Figure 24. Distribution of soil types and textures in the Coalition Service Area and average groundwater nitrate concentrations for 2009-2013.

Figure 25 shows nitrate concentrations overlaid on coarse-grained percentage for the 0 to 50 foot interval using nitrate data collected during 2009 – 2013. There is a general tendency for occurrence of relatively high nitrate concentrations in areas where the coarse-grained percentage is greater than 20%.

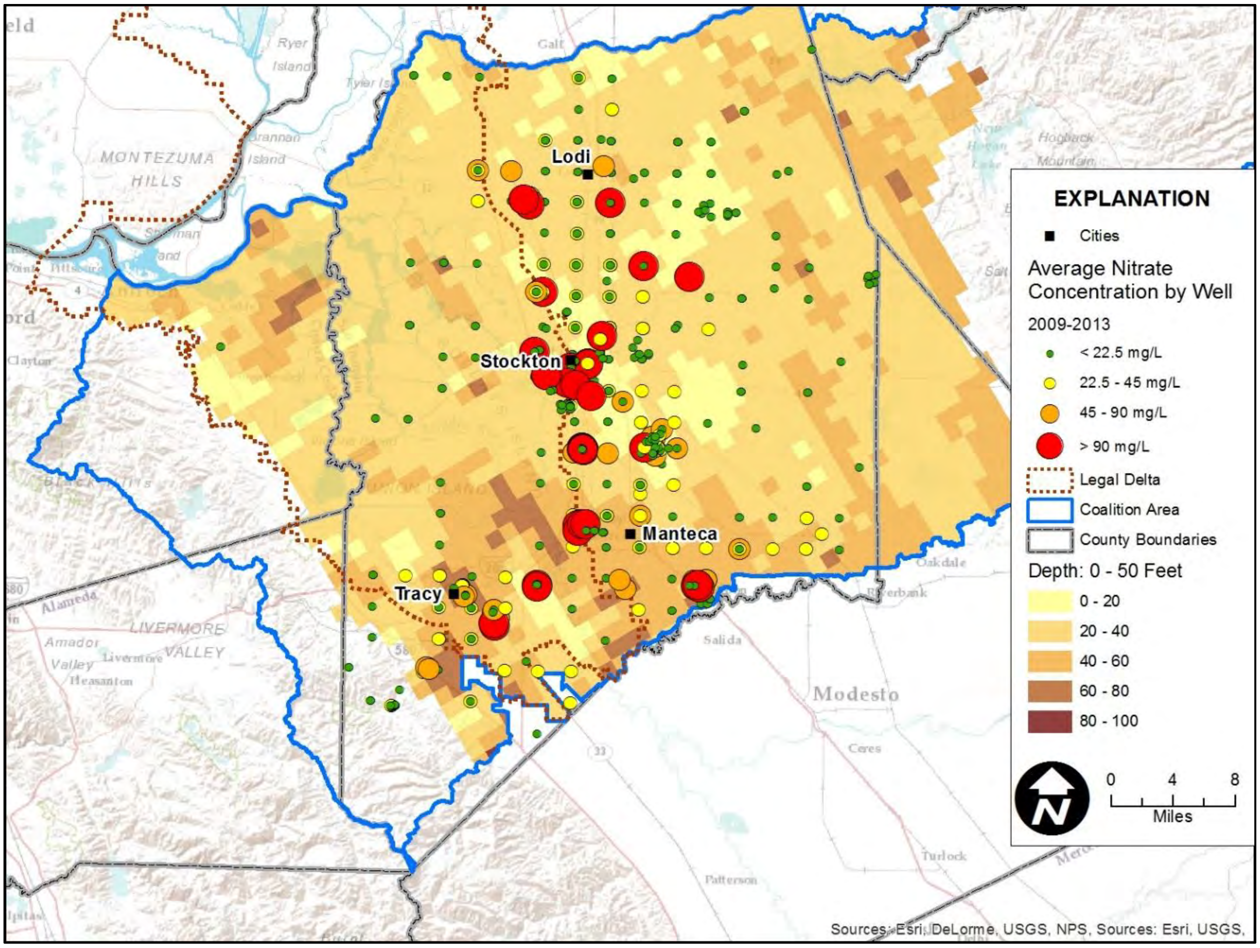

Figure 25. Percent coarse-grain sediments, 0-50 feet below land surface.

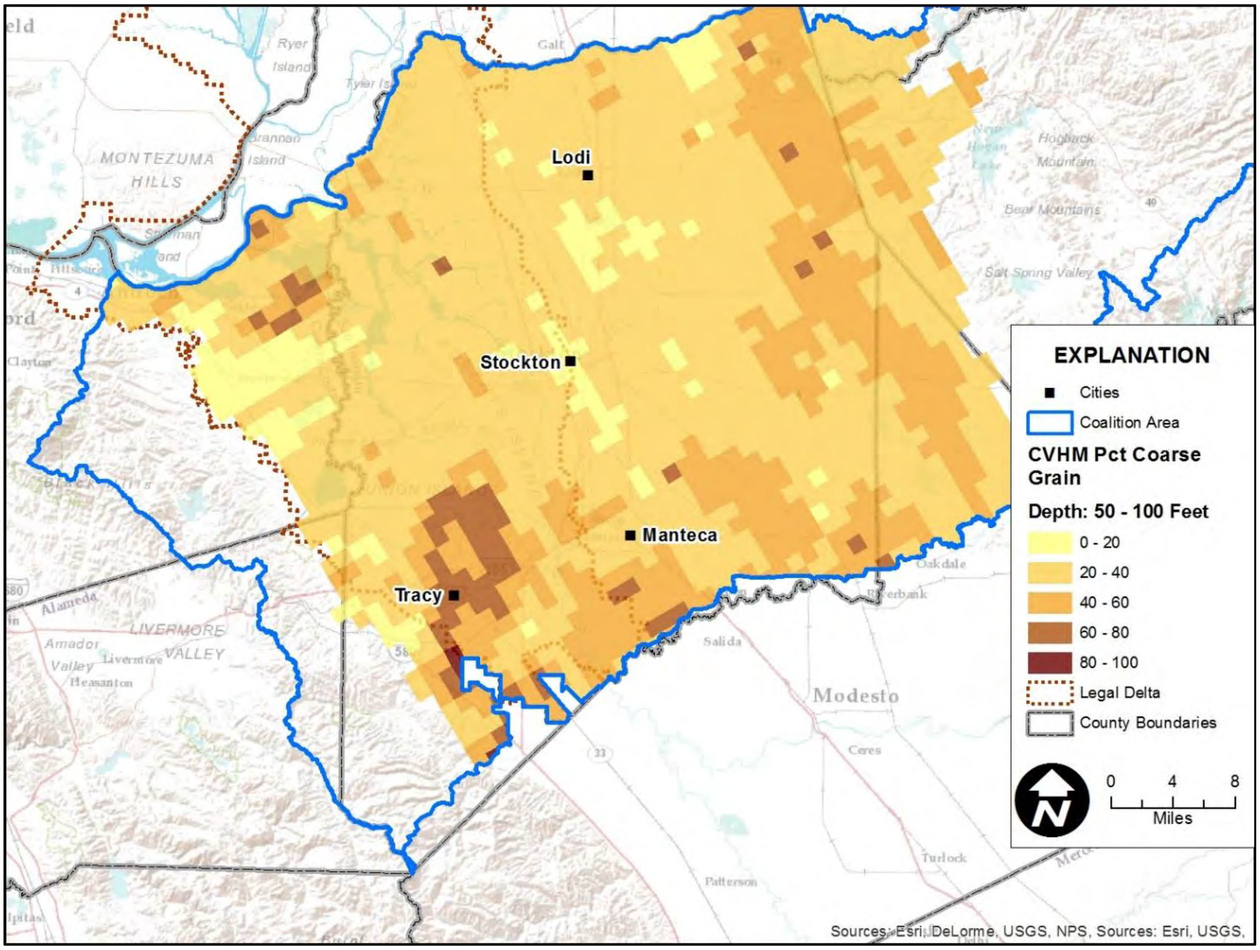

Figure 26. Percent coarse-grain sediments, 50-100 feet below land surface.

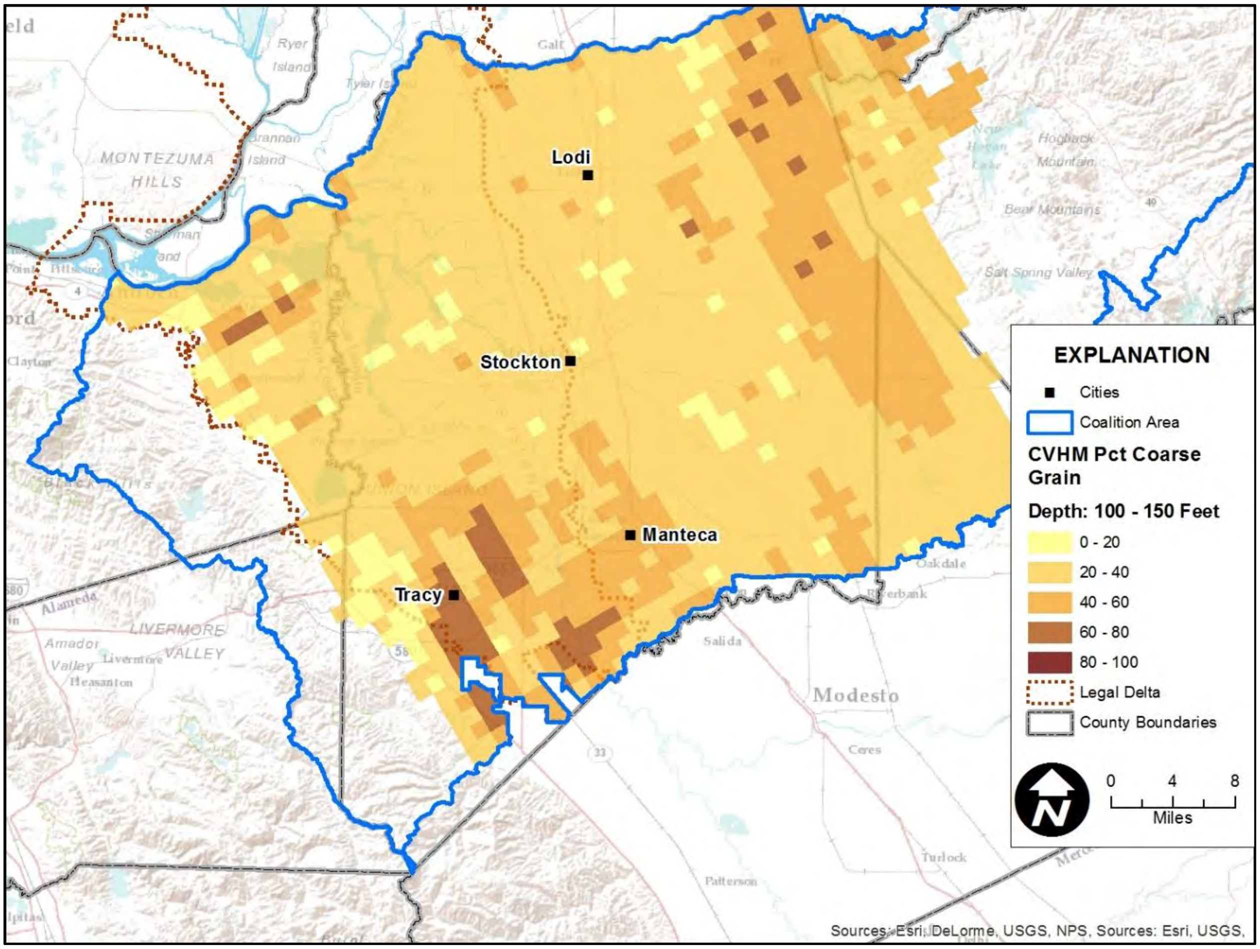

Figure 27. Percent coarse-grain sediments, 100-150 feet below land surface.

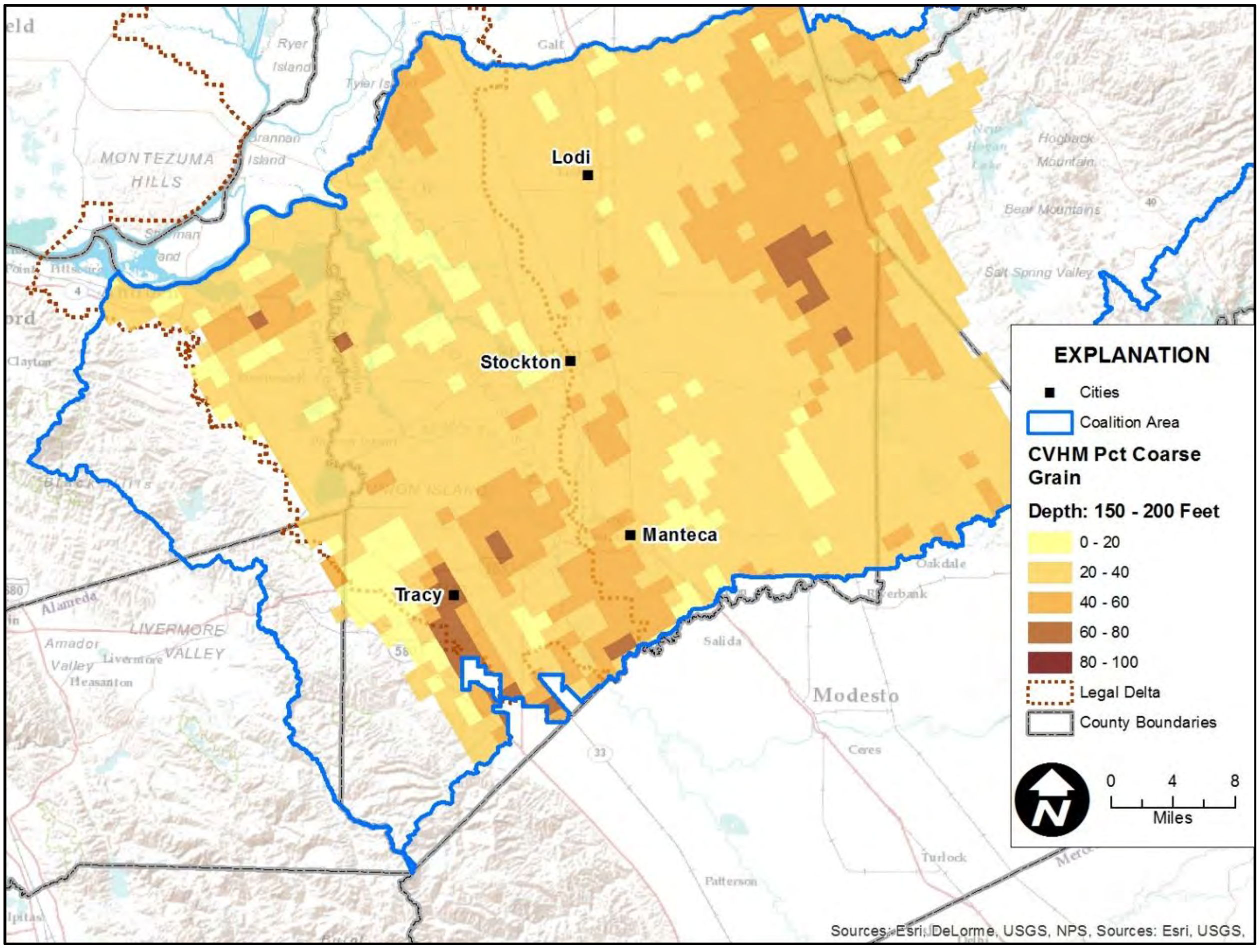

Figure 28. Percent coarse-grain sediments, 150-200 feet below land surface.

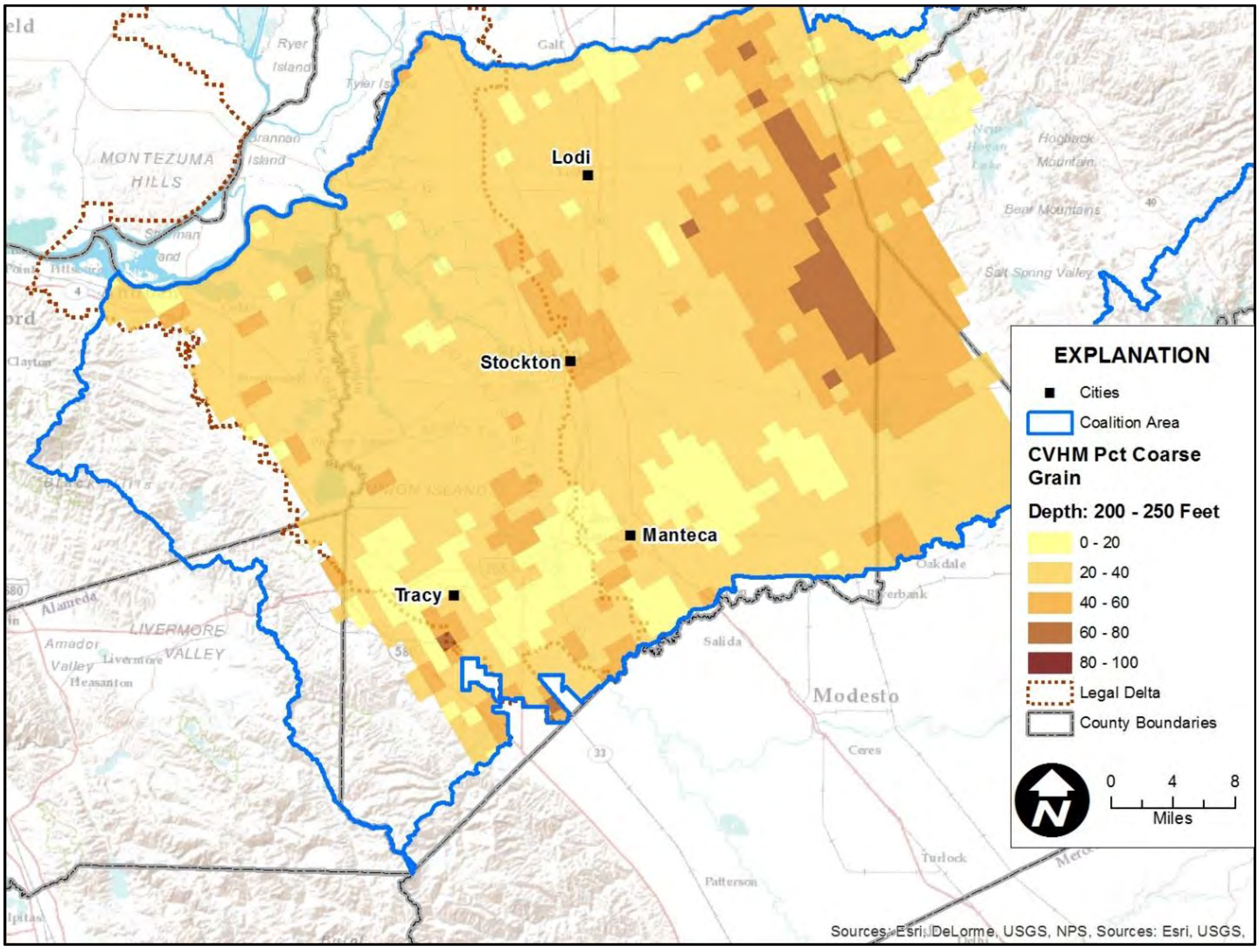

Figure 29. Percent coarse-grain sediments, 200-250 feet below land surface.

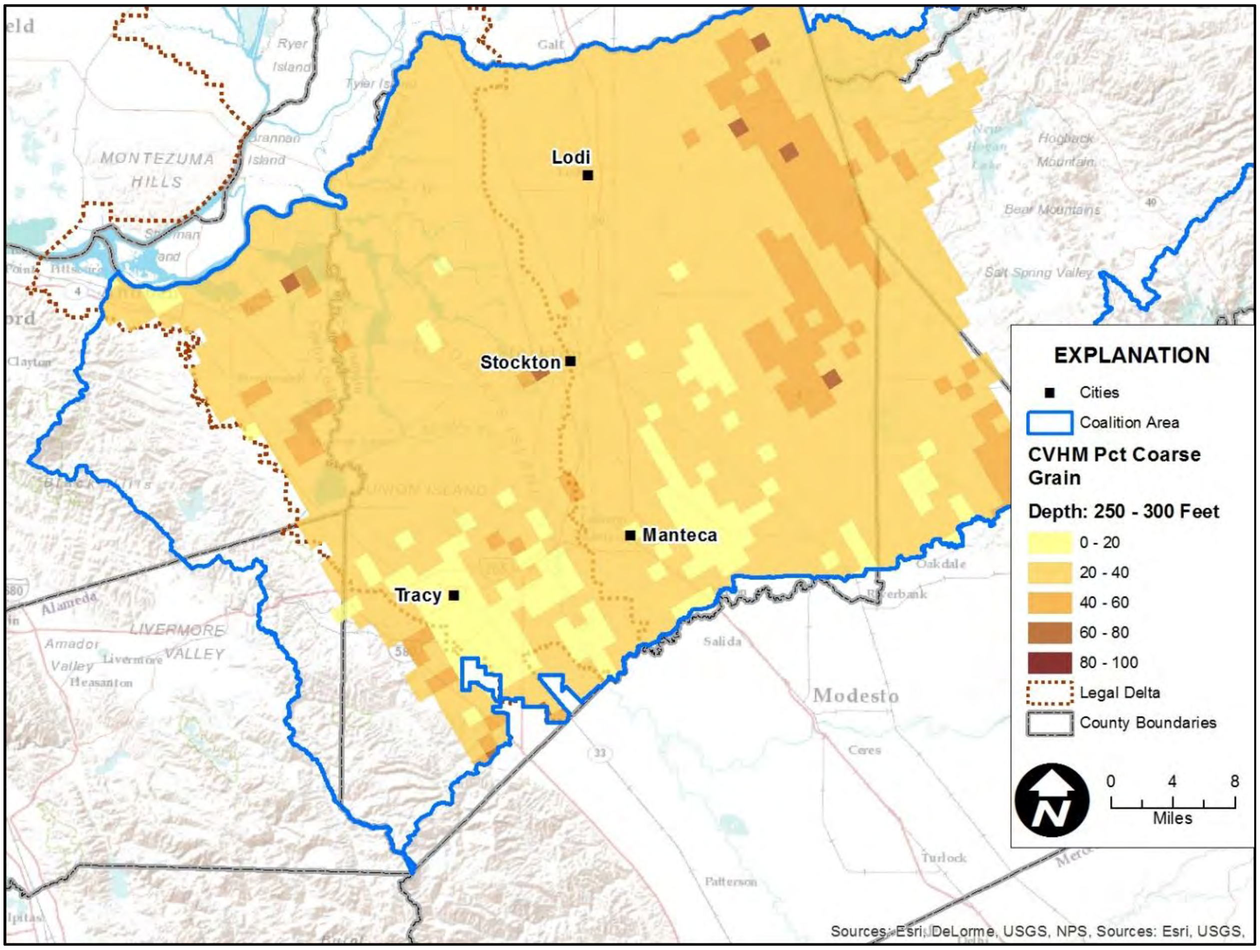

Figure 30. Percent coarse-grain sediments, 250- 300 feet below land surface.

Recharge and Contributing Areas

To estimate the spatial distribution of recharge for the Coalition Service Area, we extracted the values from the CVHM as described in the Methods Section. Figures 31 through 33 show the distribution of the recharge rates for 1994, 1995 and 2002 (the most recent estimates provided in the model). In general, net recharge rates for most of the Coalition Service Area in San Joaquin County and non-Delta areas range from -1.6 to -0.2 ft per year. The green areas indicate higher recharge rates over -0.2 ft/year. Recharge for most of the Legal Delta area is estimated to be greater than -0.2 ft/year. Negative values indicate that that there is a net loss of groundwater from the system. Figures 31 to 33 also show nitrate concentrations overlaid on mapped estimated recharge extracted from the CVHM for 1994, 1995 and 2002.

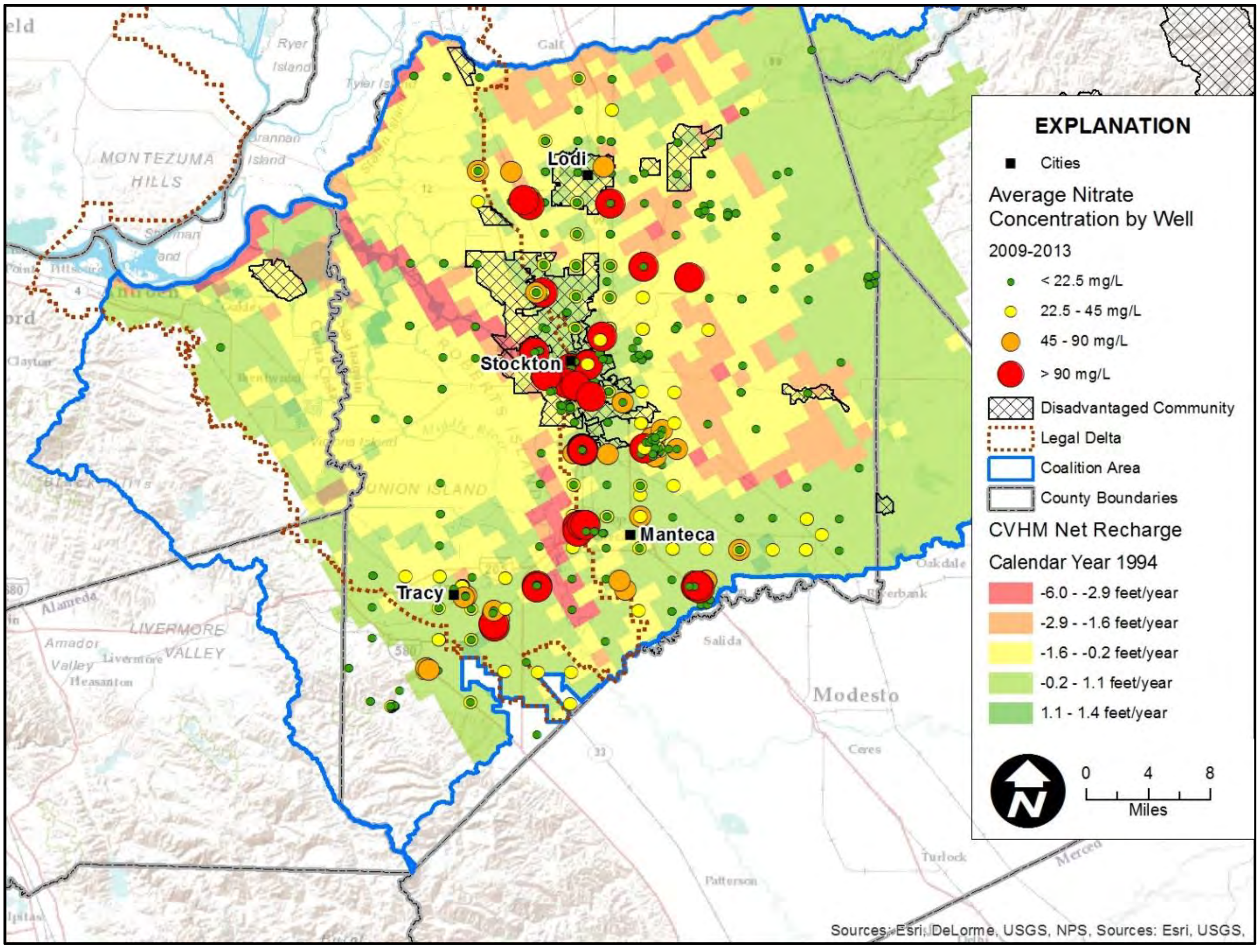

Figure 31. Estimated net recharge for 1994 and average groundwater nitrate concentrations for 2009-2013.

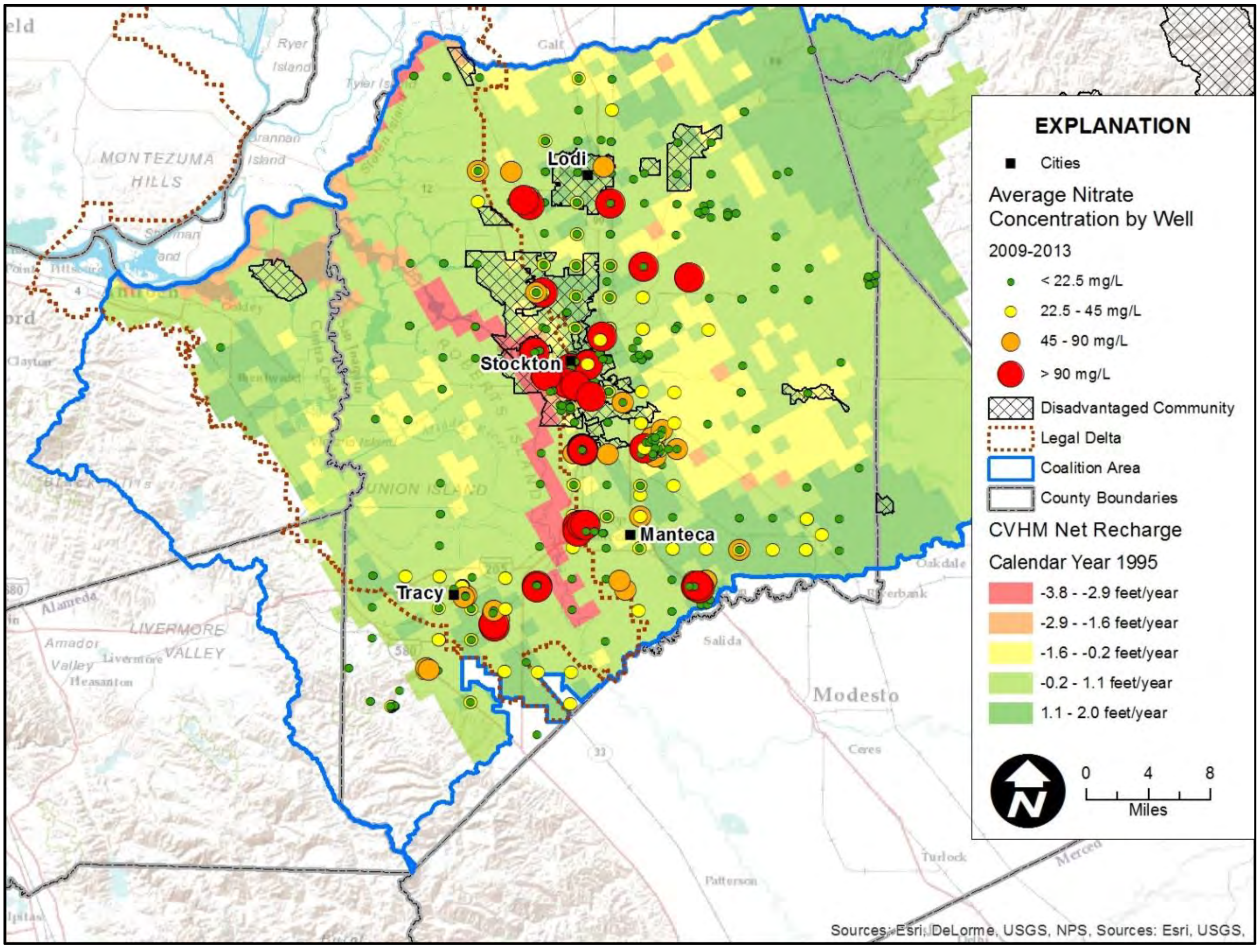

Figure 32. Estimated recharge for 1995 and average groundwater nitrate concentrations for 2009-2013.

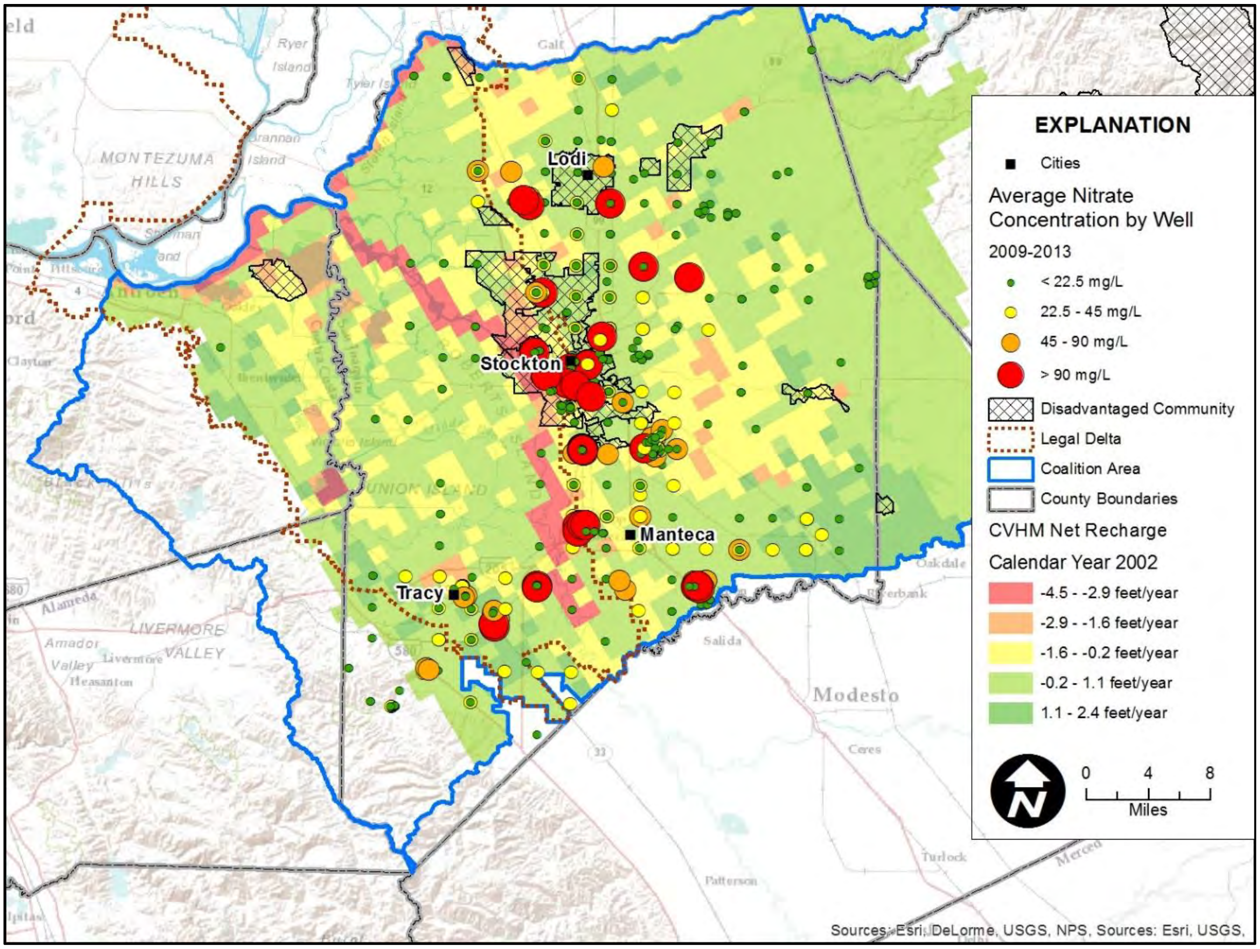

Figure 33. Estimated recharge for 2002 and average groundwater nitrate concentrations for 2009-2013.

Particle Tracking

Figure 34 shows the approximate extent of the study area, boundaries of the PWS, model grid, and model cells where starting particle locations were specified (Figure 34a) and the contributing areas identified by the cells with the simulated ending particle locations (Figure 34b). More than 1,500 particles were initially located in layer 3 of model cells underlying 50% or more of the area within the PWS boundary (the shaded model cells shown in Figure 34a). The particles either stop at the water table in model layer 1 (the model cells shaded blue in Figure 34b) or stop in up-gradient locations in the water supply aquifer (the model cells shaded pink in Figure 34b). The simulated travel distances average about 0.8 mile, and range from as little as 330 feet to 2.8 miles. Hence, the model results indicate that PWS water supply wells extract a mixture of local water table recharge and deeper groundwater. The water table recharge occurs in areas slightly up-gradient to the PWS (2 miles or less), and the deeper groundwater is recharge that enters the groundwater system further distances away.

The sensitivity of the particle tracking results to simulated groundwater velocities was tested by adjusting the specified porosity distribution. Two simulations were conducted that decreased porosity and increased groundwater velocities: (1) decreasing the specified porosity by one-half an order of magnitude (dividing the porosity values by 5); and, (2) employing the specified distribution of coarse-grained sediment in the CVHM to represent the magnitude and distribution of porosity (the fraction of coarse-grained sediment was multiplied by 25 to estimate its porosity[123] (the resulting porosity values ranged from 6 to 10%). Results are mapped in Figure 34(c) and 34(d), respectively, and show that the greater groundwater velocities calculated from these lower porosity values resulted in larger areas where water table recharge contributes to the PWS water supply. On average, the simulated travel distances increased from 1.5 to slightly more than 4 miles (4.2 miles), respectively.

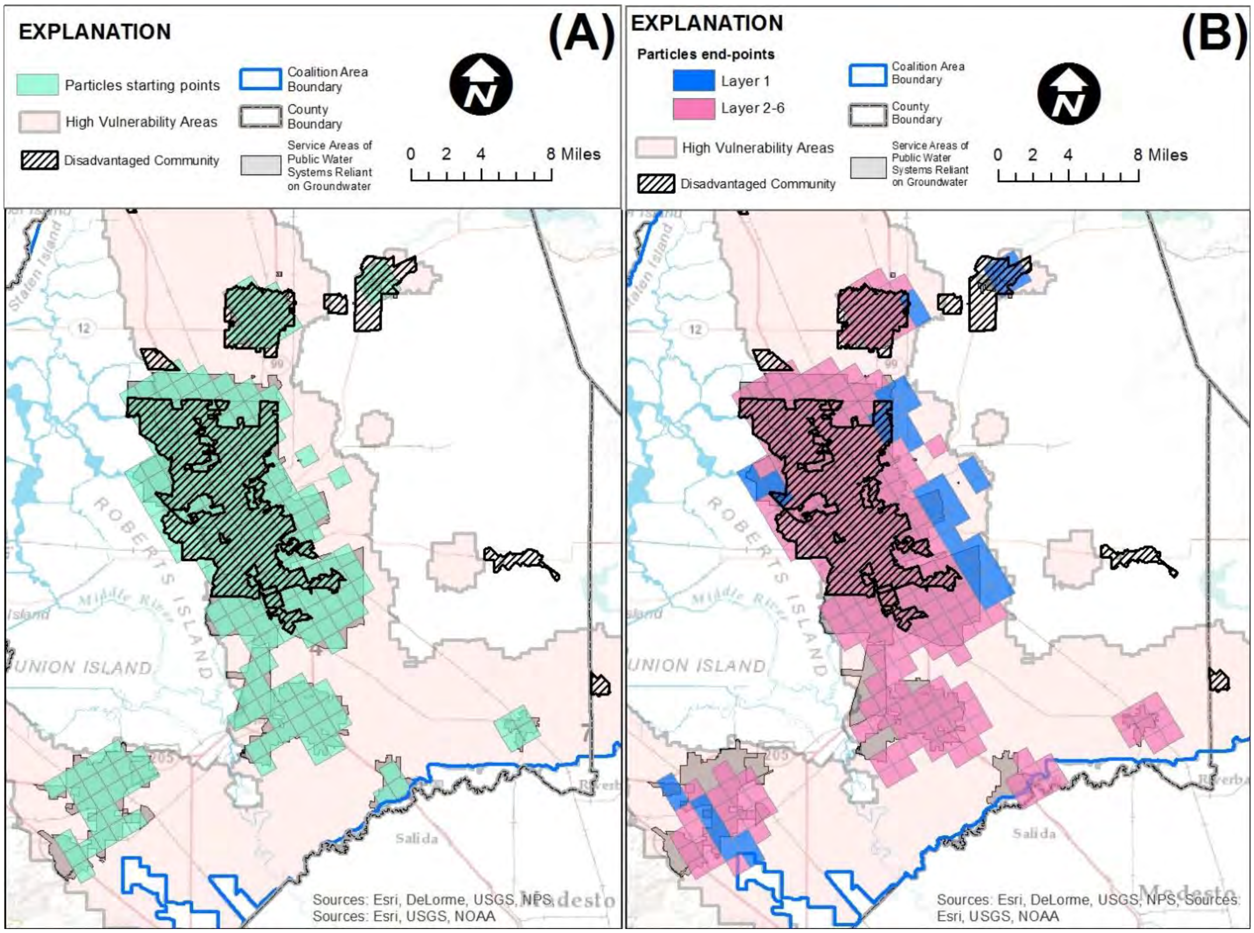

Figure 34. (a) Map showing CVHM model grid and particle starting locations; (b) Map showing results of particle tracking and recharge areas using the CVHM and contributing areas to disadvantaged communities.

[123] See footnote 4.

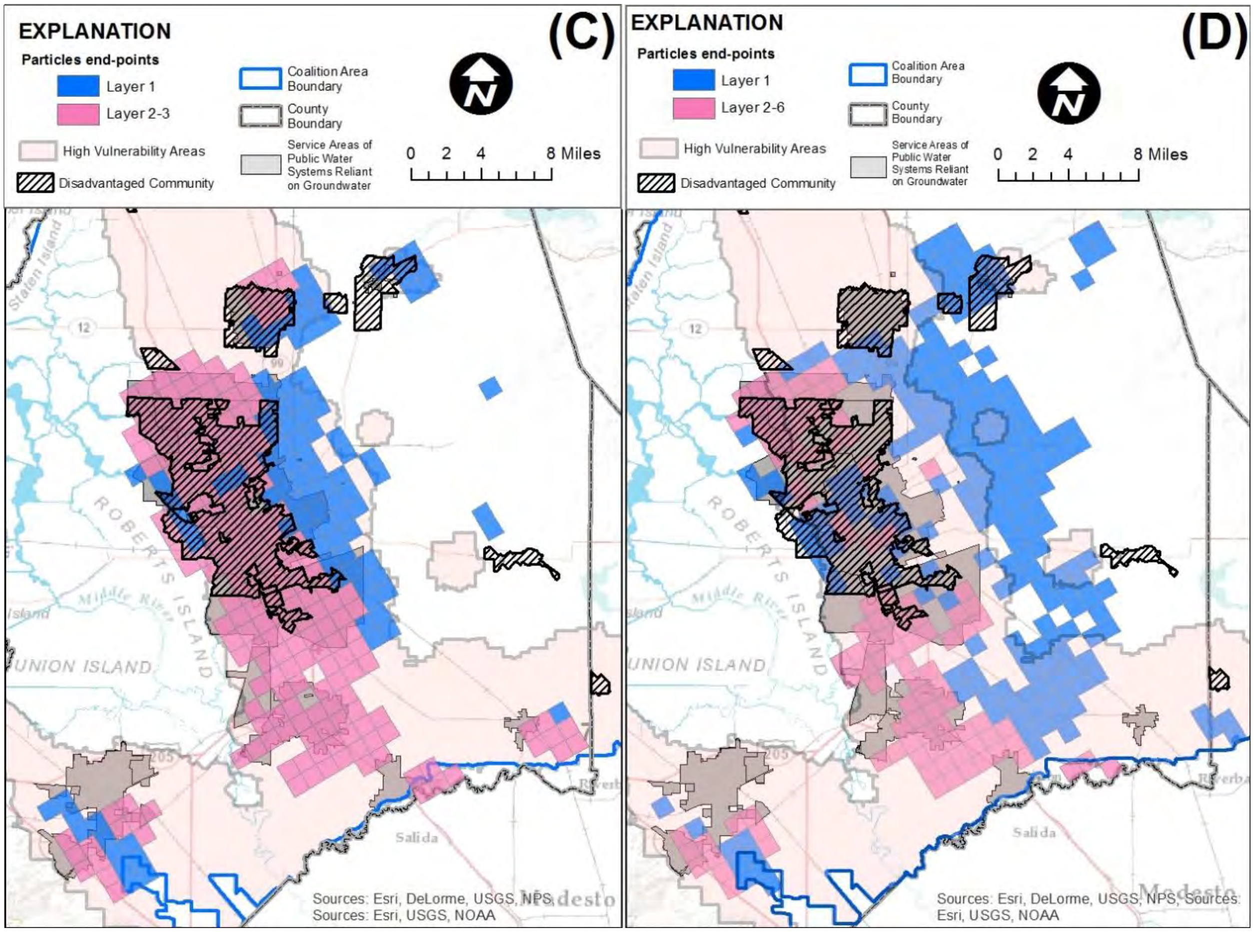

Figure 34. (c) Map showing results of particle tracking sensitivity test, decreased porosity, using the CVHM; (d) Map showing results of particle tracking sensitivity test, specified porosity distribution using the CVHM.

Regression and Covariance Analysis

We experimented with regression of maximum nitrate concentrations (dependent variable) with recharge, depth to water, fertilizer application rate, subsurface texture, and soil texture (independent variables). We estimated depth to groundwater for all wells using methods described in the Methods Section. Recharge and subsurface texture were obtained from the CVHM. We performed the multiple linear regression using combinations of 3-5 independent variables. Results of the regression models are shown in Table 12. All regression models explained a relatively small percent of the variance in nitrate concentrations (maximum R^2 was 6.2%). Due to correlation between several of the independent variables (Table 13) we selected a model using three independent variables (recharge, depth to water, and soil texture) as the optimum regression model. This regression model explained about 5.5% of the variance in nitrate concentrations and linearly related maximum groundwater nitrate concentrations in wells to depth to groundwater, recharge, and soil texture. Other combinations of three independent variables explained a smaller percent of the variance in nitrate concentrations. All regression relations were significant at the 95% confidence level.

Table 12. Results of multiple linear regression models.

Number of Independent Variables	Independent Variable					
	Recharge	Depth to Water	Fertilizer Rate	Subsurface Texture	Soil Texture	R^2
5	X	X	X	X	X	6.2%
4	X	X	X	X	--	5.8%
	X	X	X	--	X	6.0%
	X	X	--	X	X	5.7%
	--	X	X	X	X	4.5%
3	X	X	X	--	--	5.3%
	X	X	-	X	--	5.3%
	X	X	--	--	X	5.5%
	X	--	X	X	--	4.1%
	X	--	X	--	X	4.1%
	X	--	--	X	X	4.4%
	--	X	X	X	--	4.1%
	--	X	X	--	X	4.1%
	--	X	--	X	X	3.9%
	--	--	X	X	X	3.3%

X – Variable used in regression model.

Table 13. Correlation between independent variables.

Variable 1	Variable 2	Correlation Coefficient	p value
Recharge	Subsurface Texture	0.17	0.000
Recharge	Soil Texture	0.10	0.000
Depth to Water	Subsurface Texture	-0.26	0.000
Depth to Water	Soil Texture	-0.18	0.000
Subsurface Texture	Soil Texture	0.29	0.000
Fertilizer Rate	Recharge	0.08	0.003
Recharge	Depth to Water	0.05	0.048
Fertilizer Rate	Depth to Water	0.03	0.238
Fertilizer Rate	Subsurface Texture	0.02	0.582
Fertilizer Rate	Soil Texture	0.00	0.994

Measured nitrate concentrations greater than one-half the MCL and over the MCL generally correspond to the model-estimated areas for concentrations over 22.5 mg/L (one-half the MCL). However, the model missed the mark in some areas. First, in the South Delta area generally northeast of Tracy, because of the shallow water levels, the model delineated this area as having nitrate concentrations over 22.5 mg/L even though none have been measured there. Second, in the area north and northeast and southeast of Stockton, groundwater nitrate concentrations have been measured above 22.5 mg/L but are outside of the model delineated area where concentrations are greater than 50% of the MCL. The inability of the regression analysis to effectively predict areas of high nitrate concentrations, to explain a substantial portion of the variance in nitrate concentrations, or indicate significant explanatory factors or processes, led us to conclude that the distribution of groundwater nitrate concentrations may be treated for purposes of mapping as randomly distributed. Surely land- and water-management factors affect the input of nitrates to groundwater, but we opine that mapping the spatial variability for delineation of HVAs areas was more effectively accomplished using geostatistics, i.e. indicator kriging.

Use of Indicator Kriging to Preliminarily Delineate Vulnerability Areas

Maximum nitrate concentrations were used as input to the indicator kriging process. Only wells with non-urban and non-native land use classifications were used. The results of the indicator kriging analysis are shown in Figure 35. The figure shows the probability of the nitrate concentration exceeding one-half of the MCL (22.5 mg/L). Most of the wells with nitrate concentrations greater than 22.5 mg/L fall within the areas where the indicator kriging predicts there is a 40% or greater probability that nitrate concentrations exceed 22.5 mg/L. There are limited locations where wells with concentrations greater than 22.5 mg/L are located in areas where the indicator kriging map predicts less than a 40% probability that nitrate concentrations exceed 22.5 mg/L. These locations include irrigated agricultural areas northwest and northeast of Lodi, west of Stockton, and east of Tracy. At these locations, there are wells with low and high nitrate concentrations in close proximity which affects the results of the indicator kriging analysis.

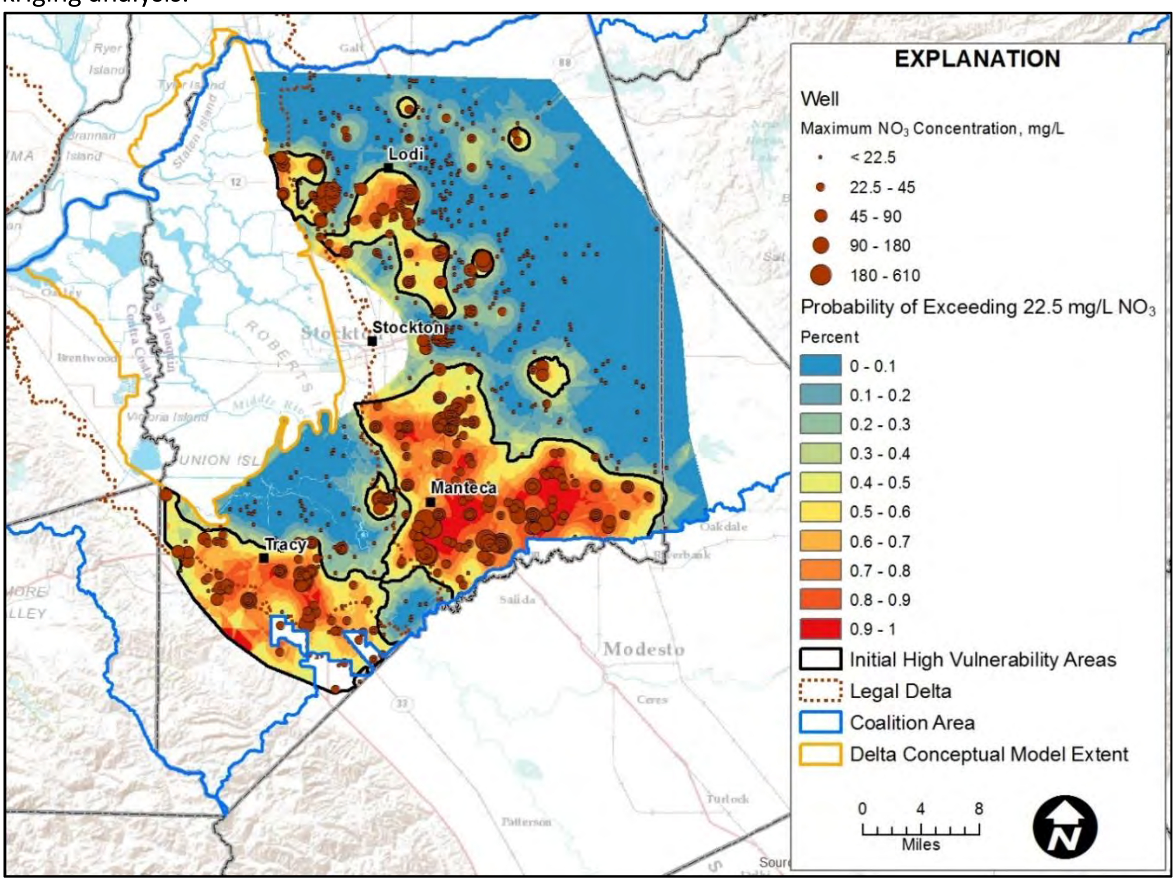

Figure 35. Maximum nitrate concentrations and probability that nitrate concentrations exceed 22.5 mg/L.

We preliminarily delineated HVAs as those areas where there is a 40% or greater probability that the nitrate concentration will exceed 22.5 mg/L (Figure 35). These areas include 92% of the wells where measured nitrate concentrations have exceeded 22.5 mg/L. Areas where nitrate concentrations have exceeded 22.5 mg/L but were not mapped within the initial HVAs are those limited areas described above where wells with highly variable nitrate concentrations are in close proximity to each other. We therefore initially expanded the HVAs to include areas where the particle tracking analysis identified recharge capture zones for the PWS and disadvantaged communities and all areas where nitrate concentrations have exceeded the MCL. The modified preliminary HVAs are shown with the nitrate dataset in Figure 35. We further modified the initial distribution of vulnerability areas based on the results of the DRASTIC analysis.

DRASTIC Results

The results of the DRASTC analysis were used to supplement the indicator kriging and particle tracking results by providing an indication of areas that are susceptible to groundwater degradation but where no groundwater nitrate concentration exceedances have been identified. Figures A5-1 through A5-8 in the Appendix show the maps of DRASTIC values for the 7 properties. As shown in Figure 19, groundwater depths generally range from 200 feet in the northeastern part of the Coalition Service Area to less than 20 feet near the Delta. Figure A5-1 in the Appendix reflects this distribution in that scores for depth to groundwater (D) increase from 1 to 10 towards the west. Recharge (R) scores (Figure A5-2 in the Appendix) reflect the highest CVHM-estimated average recharge concentrated in the southern part of the Coalition Service Area and immediately west of the Delta. Intermediate values are mapped toward the eastern boundary of the Coalition Service Area. Low values are mapped in the swath between the intermediate values in the east and high values in the south and west. We assumed that the aquifer materials are similar throughout the Coalition Service Area and thus assigned a uniform score for the “A” property.

Most of the soil (S) scores are within the intermediate range (Figure A5-4 in the Appendix) except for low scores in Stanislaus County in the southeast corner of the Coalition Service Area and east of Stockton and higher scores also east of the Stockton. Due to the low slopes throughout the Coalition Service Area, except for small areas in the eastern part of the Coalition Service Area, topography (T) scores are uniformly high (Appendix Figure A5-5) . Influence of the vadose zone (I) scores range from low to intermediate values, generally increasing from north to south and to the east (Appendix Figure A5-6). Vertical hydraulic conductivity (C) scores are generally low throughout the Coalition Service Area (Figure A5-8 in the Appendix).

The total DRASTIC scores throughout the Coalition Service Area (Figure 36) range from 50 to 167. Based on scores cited in the literature[124] and scores where there are groundwater nitrate concentrations, we classified the scores as low (50 – 110), moderate (110 – 125) and high (125 – 167). Because of the association of nitrate exceedances with areas with moderate scores, we extended the HVA to include those moderately scored areas outside the Delta (Figure 36) as well as the contributing areas delineated by the particle tracking and the DPR Groundwater Protection Zone north of Lodi (Figure 37) which was

[124] A survey of eight publications where scores were classified as low, moderate or high resulted in the following median ranges: low; 37 - 79, moderate; 80 - 100; high; 103 – 120.5. Maximum scores for low, moderate and high were 100, 150 and 150, respectively.

not included in the original HVA delineated by kriging. Groundwater Protection Zones in the southern non-Delta part (surrounding Manteca) of the Coalition Service Area (Figure 37) were originally included within the HVA.

As discussed in the Methods section, groundwater nitrate concentrations associated with hazardous waste sites were not included in the data set analyzed used for delineation of the preliminary HVA using indicator kriging. Figure A3-1 shows that all the locations of the hazardous wastes sites contaminated with nitrates listed in Table A5-1 are included within the boundaries HVA except the LLNL sites southwest of Tracy which are located in non-agricultural areas. Similarly, hazardous waste sites contaminated with pesticides in Table A5-2 are all mapped within the HVAs (Figure A3-2).

As discussed previously, the GWPA area within the Legal Delta within the Coalition Service Area is anomalous in that it overlays organic soils and, as discussed below, upward flowing groundwater. Previous evaluation of Delta soils did not fully account for texture and hydraulic conductivity. Moreover, upward flowing groundwater in this area was not accounted for. According to John Troiano, Research Scientist at DPR, the Delta GWPA area will be eliminated from future GWPA delineations. Disadvantaged Communities (DACs) and known Disadvantaged Unincorporated Communities (DUCs) are generally included within the HVAs(Figure 38).

We did not include areas with moderate scores in the south Delta in the HVA primarily because nitrate exceedances have not been observed there (Figure 36). This area is classified as moderate primarily because of the very shallow groundwater. Highly organic mineral soils in this area likely result chemically reducing conditions in this area, low groundwater nitrate concentrations and thus low vulnerability[125]. While there is little groundwater quality data in this area, the available data point absence of contaminants associated with irrigated agriculture. We could not identify any groundwater samples with pesticide detections. Available data for pesticides in the Delta indicate low potential for contamination of the shallow groundwater as represented by drain water samples[126]. Moreover, on the four Delta Wetlands islands (Webb Tract, Bouldin and Bacon islands and Holland Tract), extensive pesticide analysis was conducted in soil samples.[127] The list of analytes included those pesticides having leaching potential and that had been used on the islands which have been farmed intensely since the early 1900s[128]. No pesticide residues except for DDT were detected in subsurface soils on the four islands. Because of the high organic content of these soils, pesticides are immobile in these soils. Because of the presence of highly organic mineral soils in the South Delta area, it is therefore unlikely that pesticides will leach to the subsurface.

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[125] See Figure 1 (Distribution of percent soil organic matter in the Sacramento-San Joaquin Delta) in Deverel, Steven J, & Leighton, David A. (2010). Historic, Recent, and Future Subsidence, Sacramento-San Joaquin Delta, California, USA. *San Francisco Estuary and Watershed Science*, 8(2).: http://www.escholarship.org/uc/item/7xd4x0xw

[126] California Department of Water Resources, 1989, The Delta as A Source of Drinking Water, Monitoring Results – 1983 to 1987. DWR analyzed agricultural drainage from Delta drains for a wide spectrum of agricultural pesticides. Because pesticide concentrations in water were so far below the drinking water standards, pesticide, DWR concluded that concentrations apparently have no significant impact on use of Delta water for human consumption.

[127] Delta Wetlands Draft EIR/EIS, 1995, Appendix C6. Assessment of Potential Water Contaminants. Available at http://www.deltawetlandsproject.com/

[128] Pesticides determined in soil samples included Aldrin,aminotriazole, atrazine, dicamba, dinoseb, glyphosate, diuron, methomyl, linuron, MCPA, Monitor, carbaryl, aldicarb, 2,4-D, 2,4,5-T, dieldrin, DDT and metabolites, and methyl bromide and disulfoton

We also calculated the pesticide DRASTIC scores (see Figures A5-9 in the Appendix) which resulted in higher scores relative to the standard DRASTIC analysis. Using the same color coding as used for the standard DRASTIC results, a larger portion of the areas is characterized as highly vulnerable with scores greater than 125. However, the HVA using the standard DRASTIC methodology encompasses the areas delineated with scores greater and 140 by the pesticide DRASTIC method. DRASTIC pesticide scores ranging from 125 to 140 are generally present within the original HVA and in the area of coarse-grained soils closer the eastern boundary of the valley floor and the Coalition Service Area where sandy soils predominate (Figure 24). This area is delineated primarily as native vegetation (Figure 20). Exceptions include areas where deciduous fruits and nuts are grown adjacent to the Calaveras and Mokolumne rivers (Figures 1 and 20). These areas are characterized by relatively lower DRASTIC scores than surrounding areas (Figures 36 and A5-9).

We opine that the standard DRASTIC scores provide an adequate delineation of the HVA for the Coalition Service Area for the following reasons. Pesticide analysis results included here show that the HVA based on standard DRASTIC scores adequately encompasses areas where there are pesticide exceedances and detections and DPR Groundwater Protection Areas (Figure 37). Also, pesticide detections have decreased with time in the Coalition Service Area. An exception includes DBCP exceedances in the area east of Lodi. As noted previously, DBCP was omitted from DPR's determination of Groundwater Protection Areas because of its lack of use and extremely long half-life. This justifies the exclusion of this area from the HVA.

We further opine that inclusion of native vegetation areas in the HVA at this stage is inconsistent with the purposes of the GAR which is to "Provide a basis for establishing workplans and priorities to evaluate the effectiveness of agricultural management practices to protect groundwater quality; and provide a basis for establishing groundwater quality management plans in high vulnerability areas and priorities for implementation of those plans." Since there is minimal agriculture in these areas mapped as native vegetation, the Coalition cannot reasonably be expected to develop management practices. In summary, we agree with the consensus opinion of the Groundwater Monitoring Advisory Workgroup[129]: "that the most important constituents of concern related to agriculture's impacts to the beneficial uses of groundwater are nitrate and salinity. In addition to addressing the widespread nitrate problems, the presence of nitrates in groundwater at elevated levels would serve as an indicator of other potential problems associated with irrigated agricultural practices."

[129] Steve Deverel is a member of the Groundwater Monitoring Advisory Workgroup

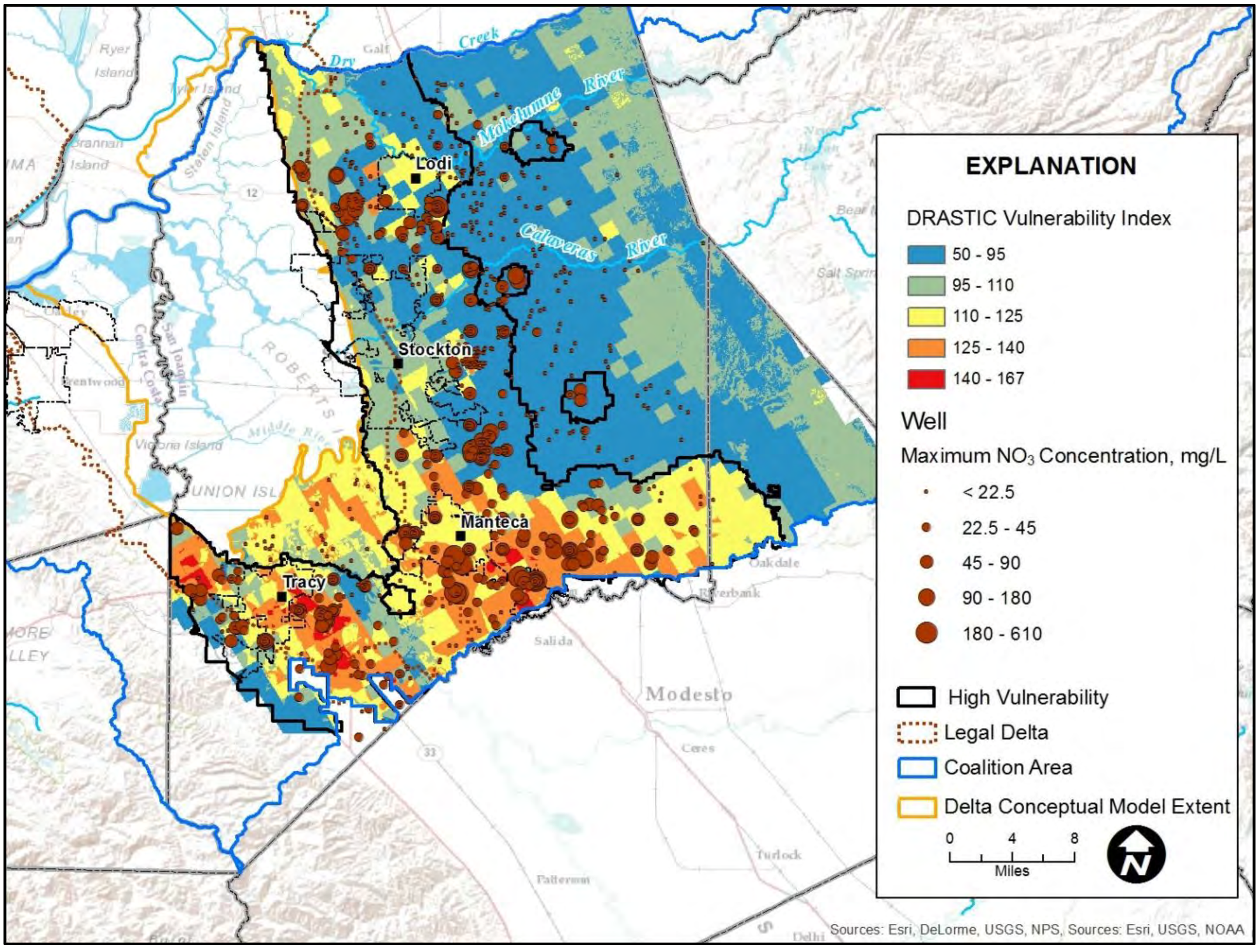

Figure 36. DRASTIC scores and revised HVAs and maximum nitrate concentrations.

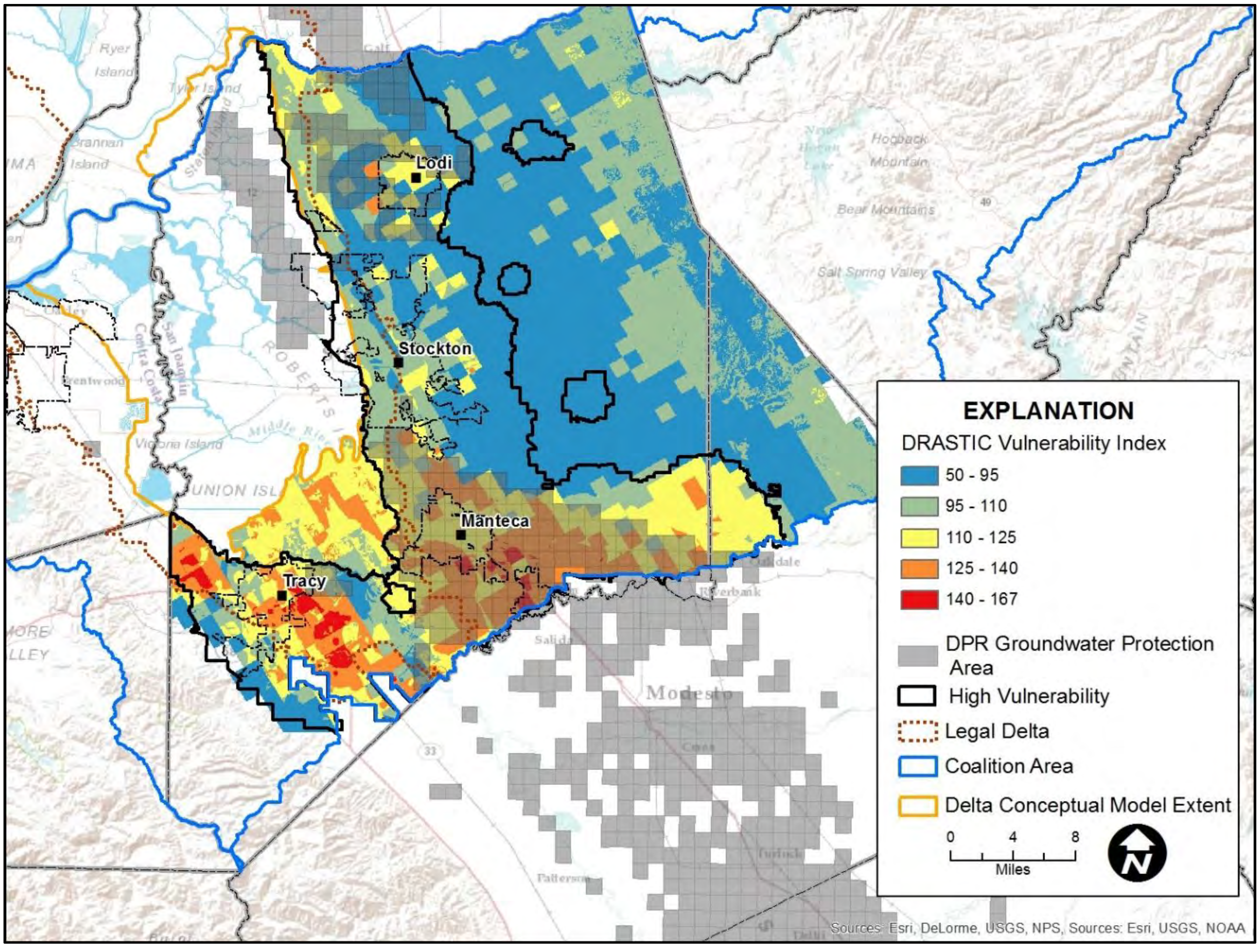

Figure 37. DRASTIC scores and revised high HVAs and DPR Groundwater Protection Areas.

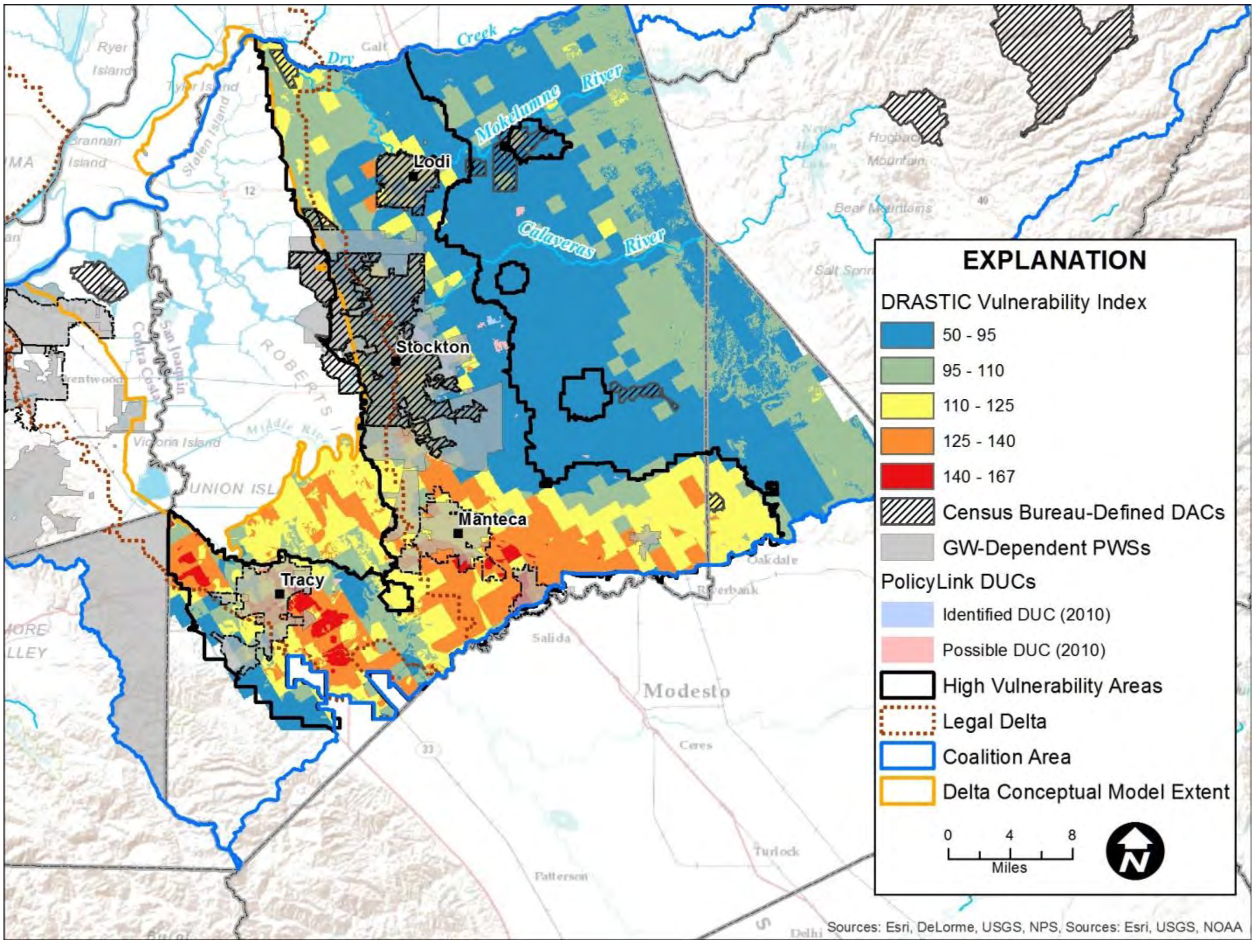

Figure 38. DRASTIC scores and revised HVAs and disadvantaged communities (DACs) and disadvantaged unincorporated communities (DUCs).

The HVAs are shown with 2009-13 average nitrate concentrations in Figure 39. All except one well with 2009-13 average nitrate concentrations over 22.5 mg/L are located within the HVAs. Figure 40 shows the HVAs with nitrate concentrations trends (see Nitrate Trends section in Appendix for nitrate concentration graphs). All wells with increasing nitrate concentrations are located within the HVAs.

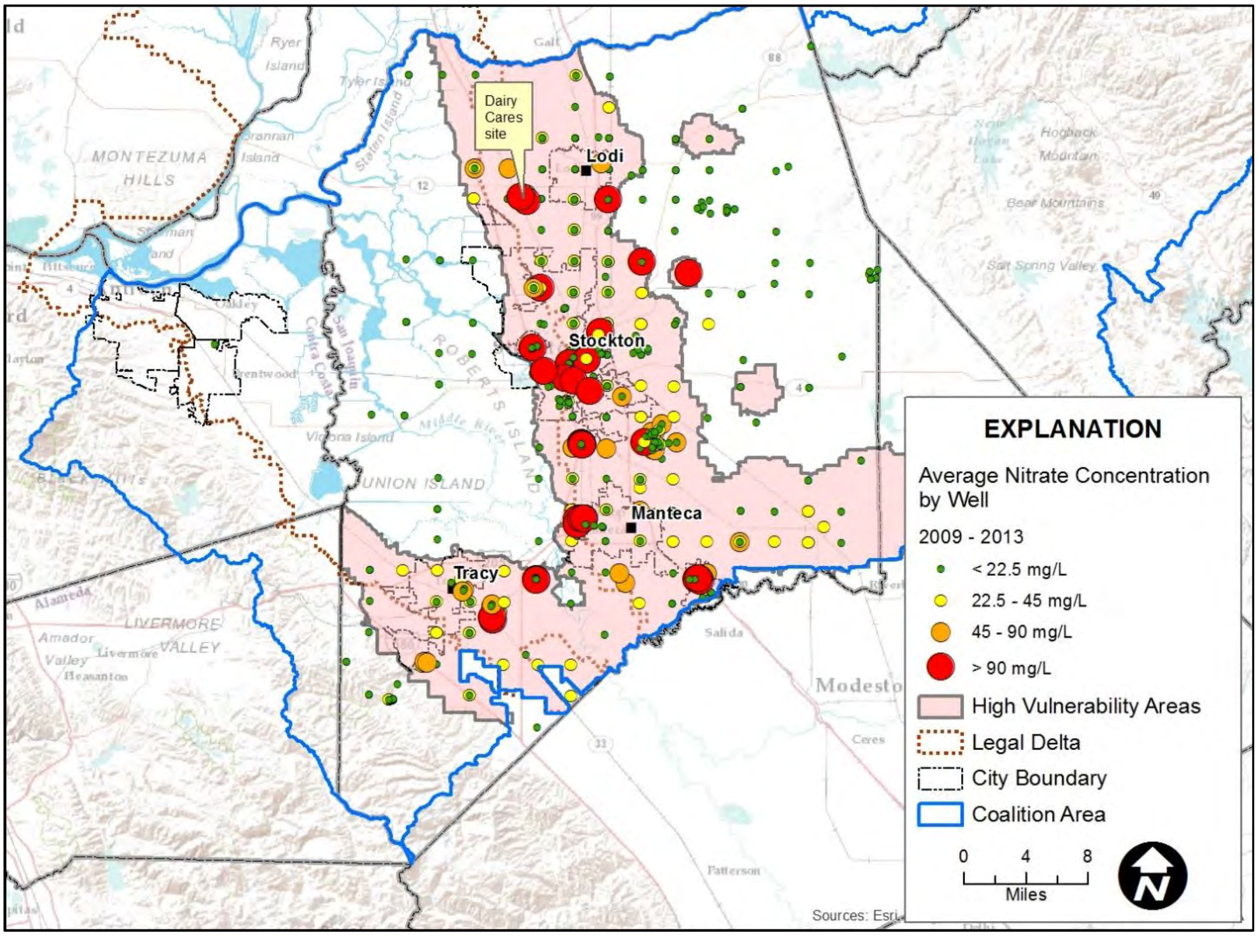

Figure 39. The HVAs and 2009-13 nitrate concentrations.

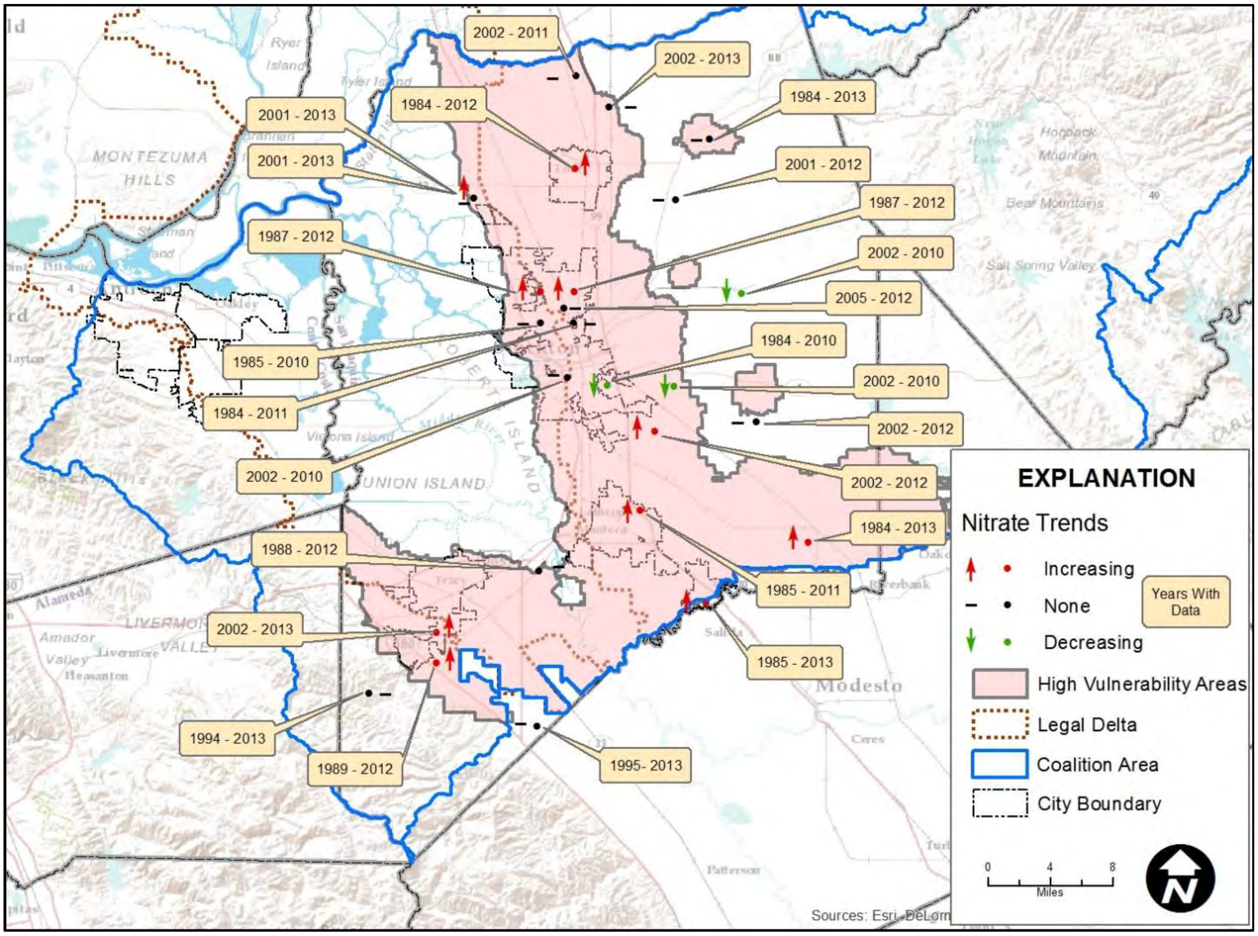

Figure 40. The HVAs and nitrate concentration trends.

The HVAs are shown with 2009-13 TDS concentrations in Figure 41. The recommended secondary drinking water standard for TDS is 500 mg/L and the upper limit is 1,000 mg/L.; 386 of 423 wells with TDS > 500 mg/L (recommended limit) are located in the HVAs. Similar to nitrate concentrations, many wells with TDS concentrations above the recommended limit are located in Stockton and Lathrop urban areas. There are also wells with TDS concentrations above the recommended limit on the eastern edge of San Joaquin County and in the Delta on Staten and Roberts islands. There is the potential for high salinity in deeper wells in the eastern Delta[130]. Figure 42 shows HVAs with TDS trends (see Total Dissolved Solids Trends section in Appendix for TDS concentration graphs). All wells with increasing TDS trends are within the HVAs.

[130] For example, in the 1980s water from a well drilled to about 300 feet on western Terminous was high in salt (5,900 - 6,700 mg/L). See G. J. Hoffman, E. V. Maas, T. L. Prichard, and J. L. Meyer, 1983, Salt tolerance of corn in the Sacramento-San Joaquin Delta of California, Irrigation Science, 4:31-44

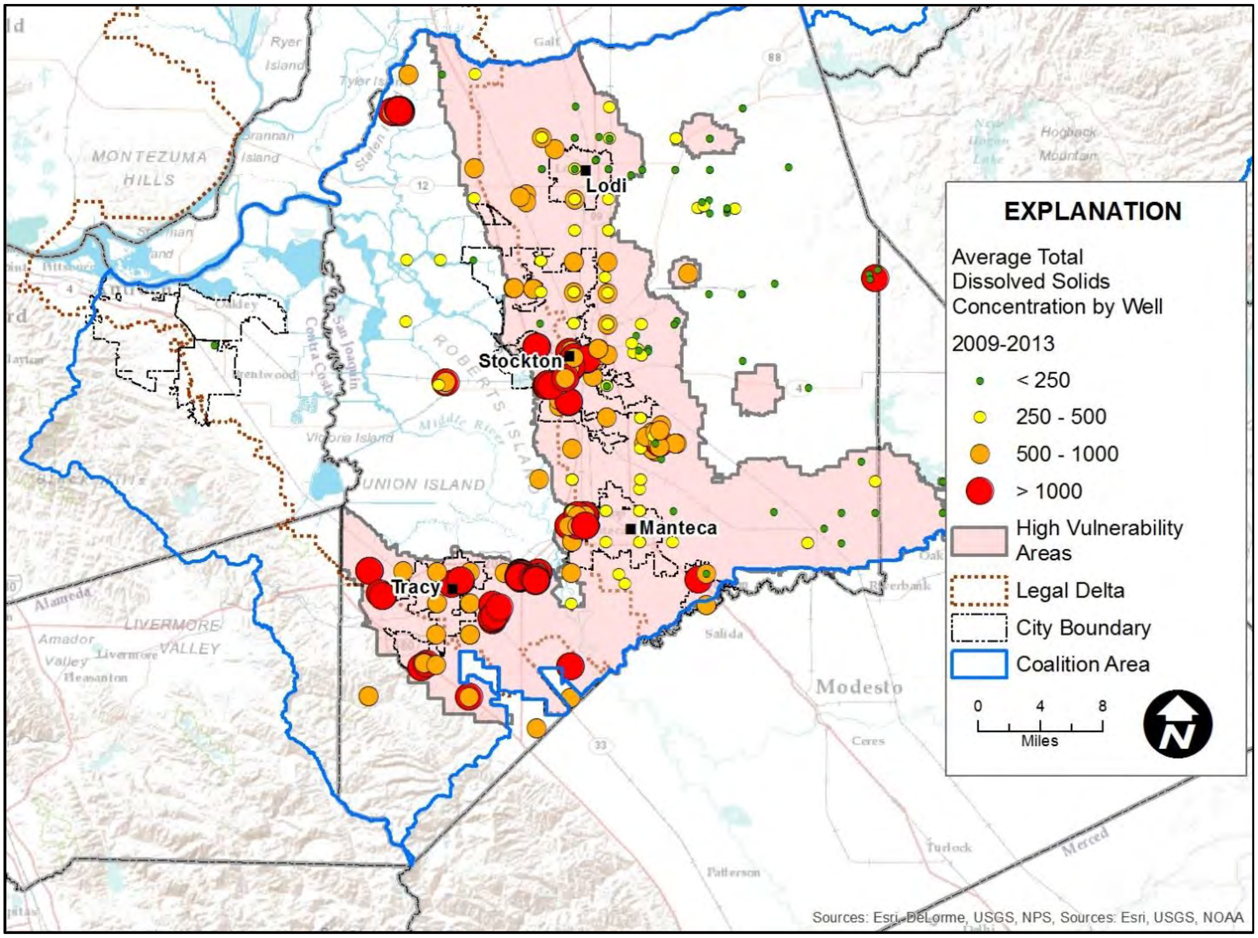

Figure 41. The HVAs and 2009-13 TDS concentrations.

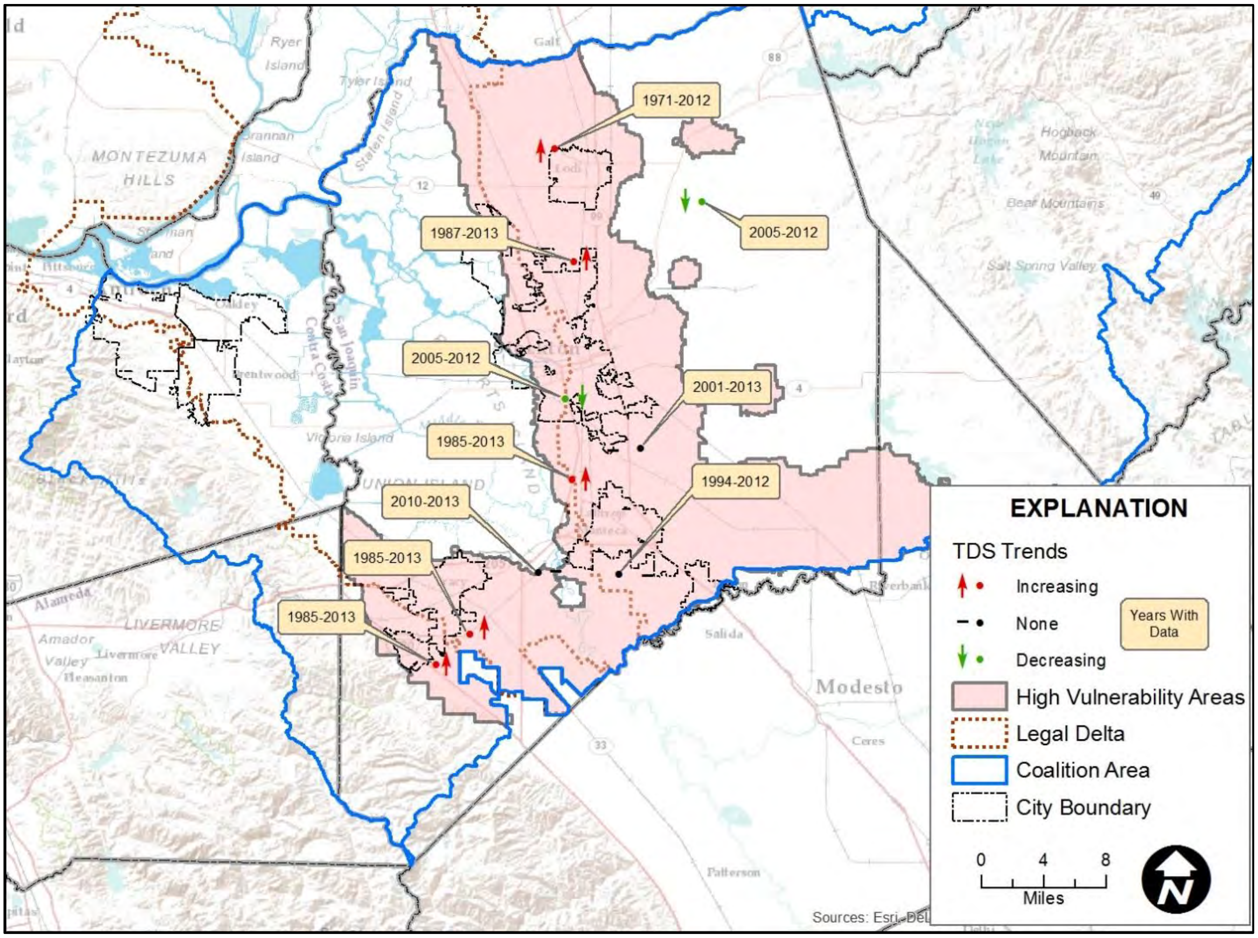

Figure 42. The HVAs and TDS concentration trends.

The HVAs are shown with 2009-13 arsenic concentrations in Figure 43. Eighty percent of the wells with concentrations above the MCL (10 ug/L) are located within the HVAs. Wells with concentrations above the MCL outside the HAVs are located in the Delta, and the hills southwest of Tracy delineated as native vegetation.

The available data (in our database) indicate that arsenic concentrations are influenced by oxidation and reduction conditions and pH (Figures 44 and 45). Consistent with data presented in Izbicki and others[131] for the Coalition Service Areas and the literature, relatively high arsenic concentrations are associated with low dissolved oxygen and relatively high pH values and not related to agricultural practices. Adsorption and co-precipitation of arsenic by clay minerals and metal oxides are the predominant solubility controls in oxidized environments[132]. Both the pentavalent arsenate and trivalent arsenite are adsorbed on oxide minerals. The adsorption behavior is pH- and species dependent; at low pH arsenate

[131] Izbicki and others, see footnote 22.

[132] Hem, J. D., 1977, Reactions of metal ions at surfaces of hydrous iron oxide, Geochem. Cosmochim, Acta, 41, 527-538; Leckie, J. O., Benjamin, M. M., Hayes, K., Kaufman, G., and Altmann, S., 1980, Adsorption/coprecipitation of trace elements from water with iron oxy-hydroxide, Electric Power Research Institue Report CS-1513, Stanford University, CA; Pierce, M. L., and Moore, C. B., 1980, Adsorption of arsenite on amorphous iron hydroxide and dilute aqueous solutions, Environmental Science and Technology, 14, 214-216.

is adsorbed to a greater extent, while arsenite is adsorbed at relatively higher rates at high pH[133]. Leckie and others[134] demonstrated that the pentavalent arsenate present in aerobic aqueous environments strongly adsorbs on amorphous iron oxyhydroxides below pH 8. In chemically reducing environments, the trivalent form predominates which does not adsorb as strongly as the pentavalent form. Also, under reducing conditions, iron oxides are more soluble as ferrous iron is reduced to ferric iron. Therefore, dissolution of the adsorbate (iron oxides) and less adsorption of the trivalent arsenite species results in higher concentrations under aerobic or chemically reducing conditions.

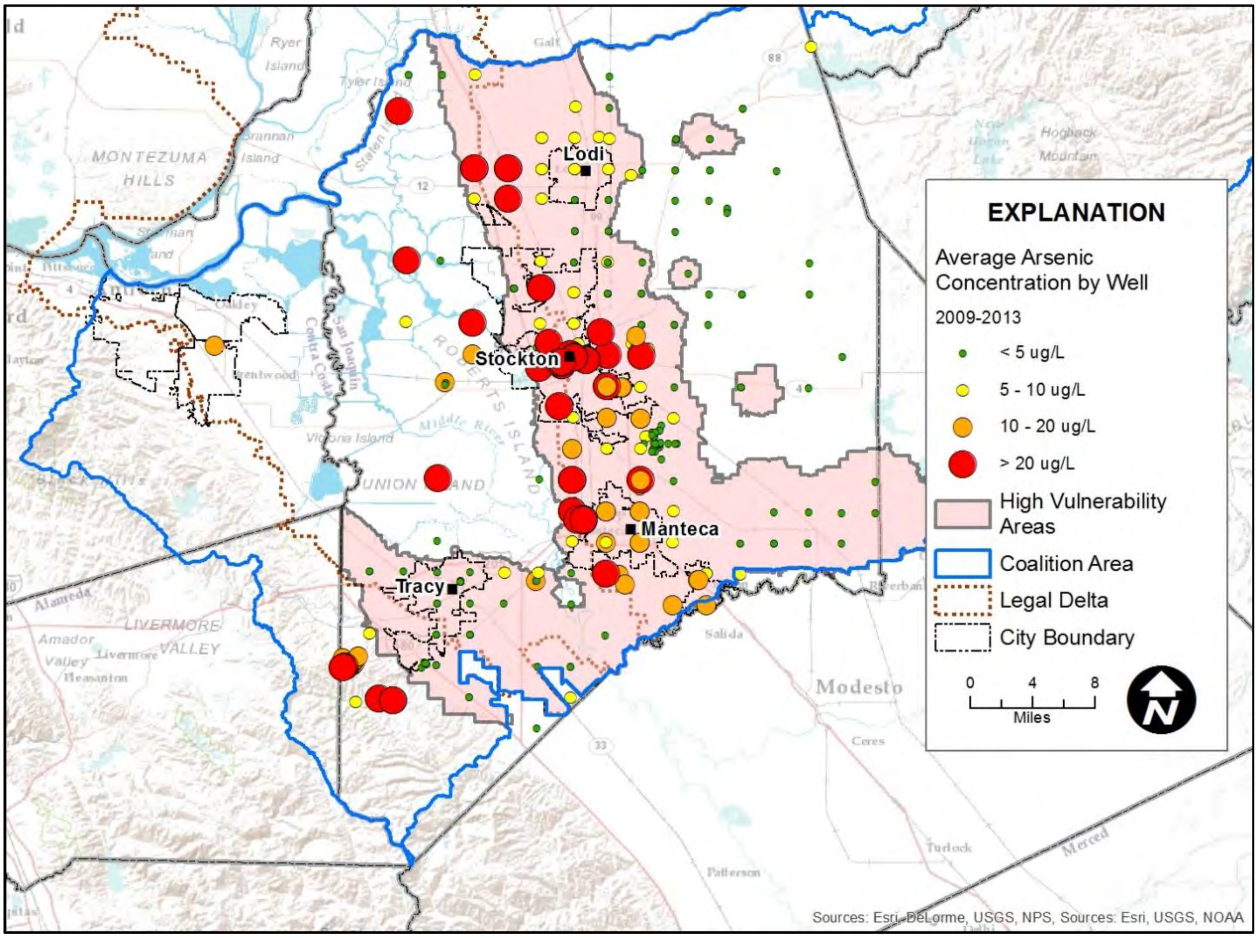

Figure 43. The HVAs and 2009-13 arsenic concentrations.

[133] Raven, K. P., Jain, A., and Loeppert, R. H., 1998, Arsenite and arsenate adsorption on ferrihydrite: Kinetics, equilibrium, and adsorption envelopes, Environmental Science and Technology, 32, 344-349.

[134] Leckie and others, see footnote 132.

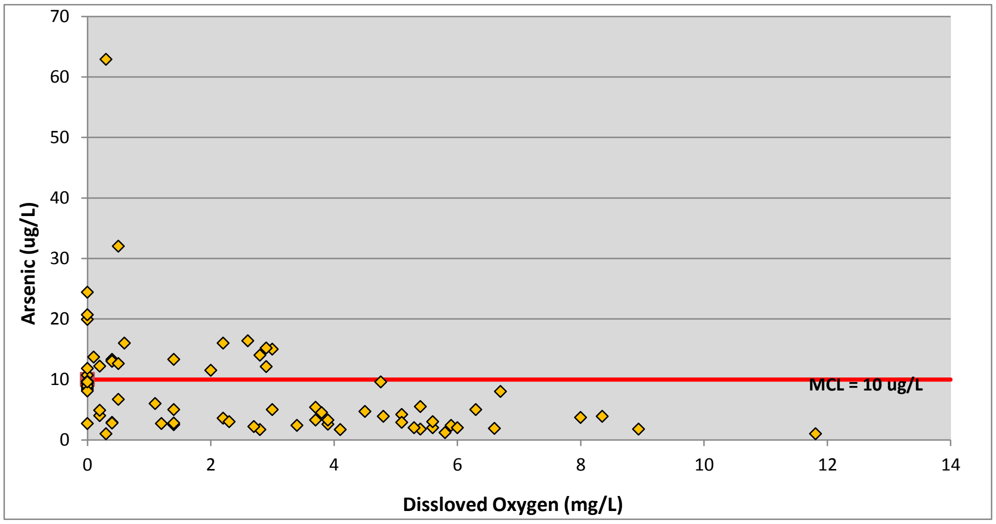

Figure 44. Relation of arsenic concentrations to dissolved oxygen.

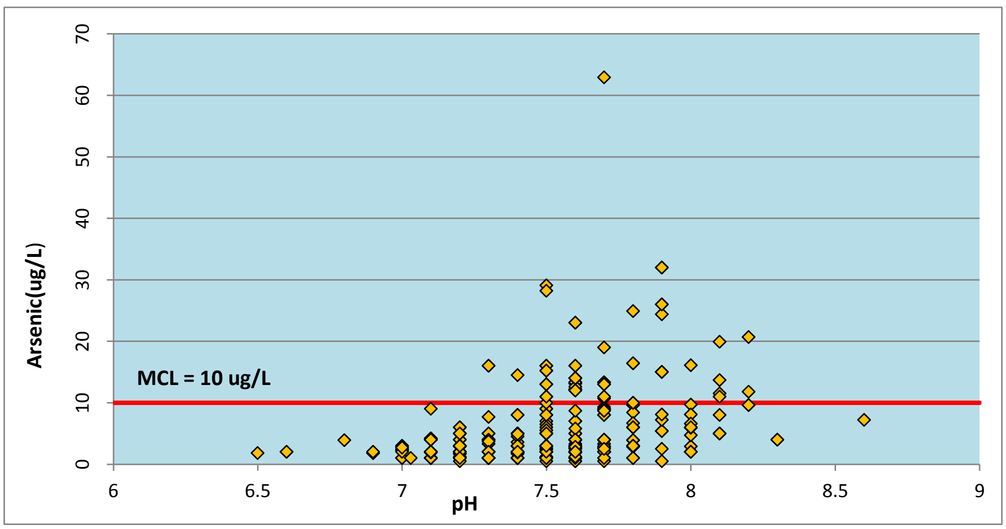

Figure 45. Relation of arsenic concentrations to pH.

The HVAs are shown with 2009-13 boron concentrations in Figure 46. Eighty-nine percent of the wells with 2009-13 boron concentrations greater than 1.0 mg/L are within the HVAs (Figure 44). The majority of these wells are within the City of Tracy boundary. There were also boron concentrations over 1.0 mg/L within Stockton City limits, on Staten Island and the areas delineated as native vegetation southwest of Tracy. Most wells with moderately high concentrations (0.2 – 1.0 mg/L) are located in the Stockton and Lathrop urban area and in the Delta. The primary water-quality concern for boron is plant sensitivity to concentrations over about 1 mg/L in irrigation water.[135]

[135] W. P. Chen, A. C. Chang Page, A.L., 2012, Deficiencies and toxicities of trace elements, In (Wallender, W.W. and Tanji, K.K), ed.) Agricultural Salinity Assessment and Management, ASCE Manual of Practice 7, Second Edition.

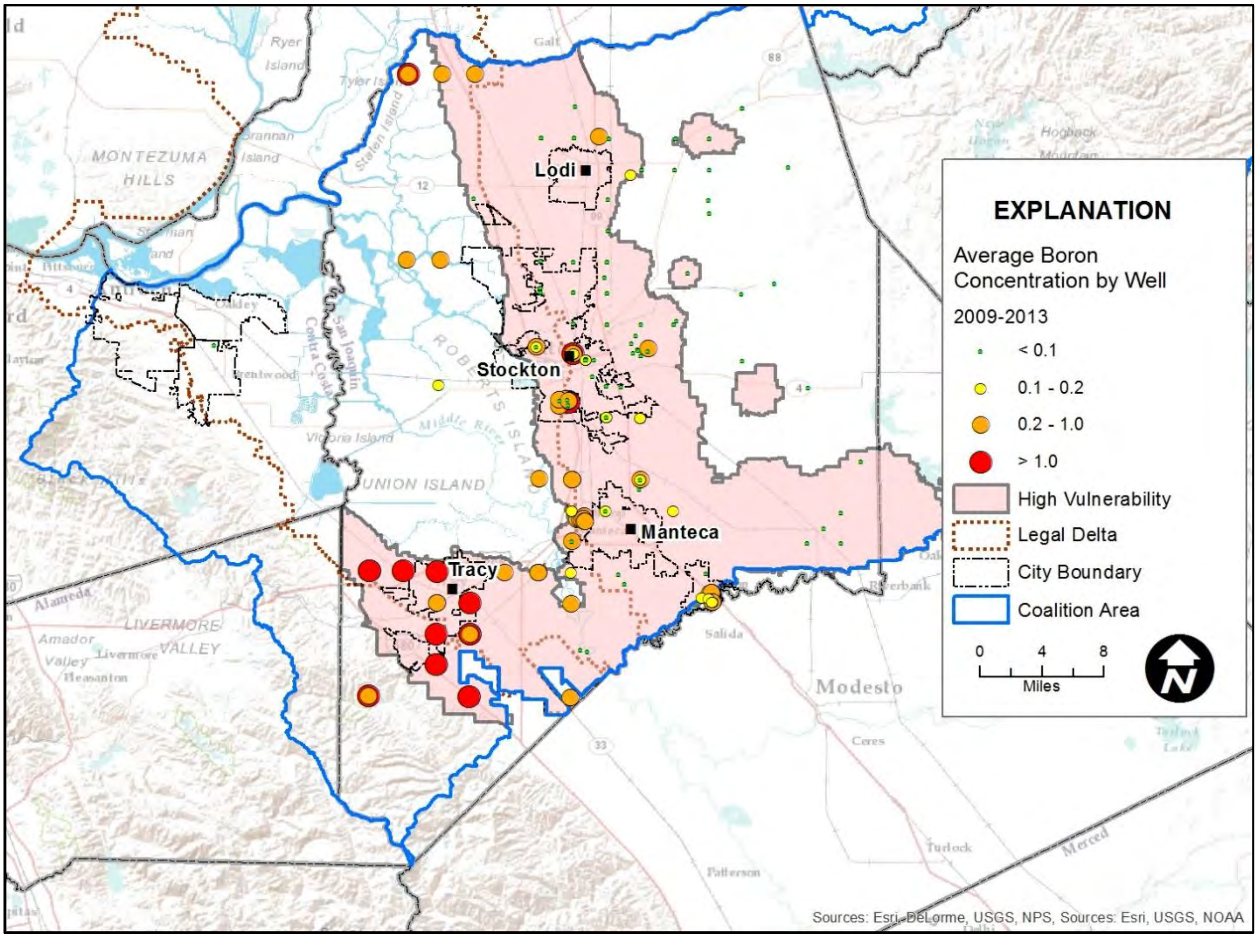

Figure 46. The HVAs and 2009-13 boron concentrations.

Three pesticides were detected in wells in the Coalition Service Area; the soil fumigants ethylene dibromide (EDB) and di-bromo-chloro-propane (DBCP), and the herbicide Simizine. Maps of pesticide detections in the Appendix show that Simizine and EDB exceedances were non-existent in recent years and DBCP is the primary pesticide detected. The HVAs are shown with maximum 2013 (DBCP) concentrations in Figure 47. All except one cluster of wells with 2013 DBCP detections are located within the HVA. This well cluster with the maximum concentrations over 0.4 ug/L is located east of Lodi, outside the HVAs. Maps depicting yearly maximum and average DBCP concentrations from wells sampled between 2009 and 2013 can be found in the Appendix. Wells with maximum DBCP concentrations that exceeded the MCL decreased from 49 wells in 2009 to nine wells in 2013.

The pesticide DBCP has been banned for use in California since 1979. Due to its widespread use, high rates of application and an extraordinarily long half-life of over 100 years, DPR considered DBCP to be an extreme case and not reflective of present-day land use as detection in wells have likely resulted from movement of groundwater to a greater extent than other pesticides. The DPR therefore excluded DBCP from the analysis that led to the development of GWPAs[136].

[136] Troiano et al, 1999, see footnote 56

In 2013, all wells sampled for ethylene dibromide (EDB) within the Coalition Service Area had concentrations which fell below the drinking water MCL of 0.05 ug/L. Maps depicting yearly maximum and average EDB concentrations from wells sampled between 2009 and 2013 can be found in the Appendix. Maximum EDB concentrations sampled in wells decreased significantly over time; 15 wells in 2009 had EDB concentrations which exceeded the MCL whereas no wells in 2013 exceeded the MCL. There were only a few wells where Simazine was detected in 2009 and 2010 and all wells had detections below the drinking water MCL of 4 ug/L. Maximum and average Simazine concentration maps can be found in the Appendix.

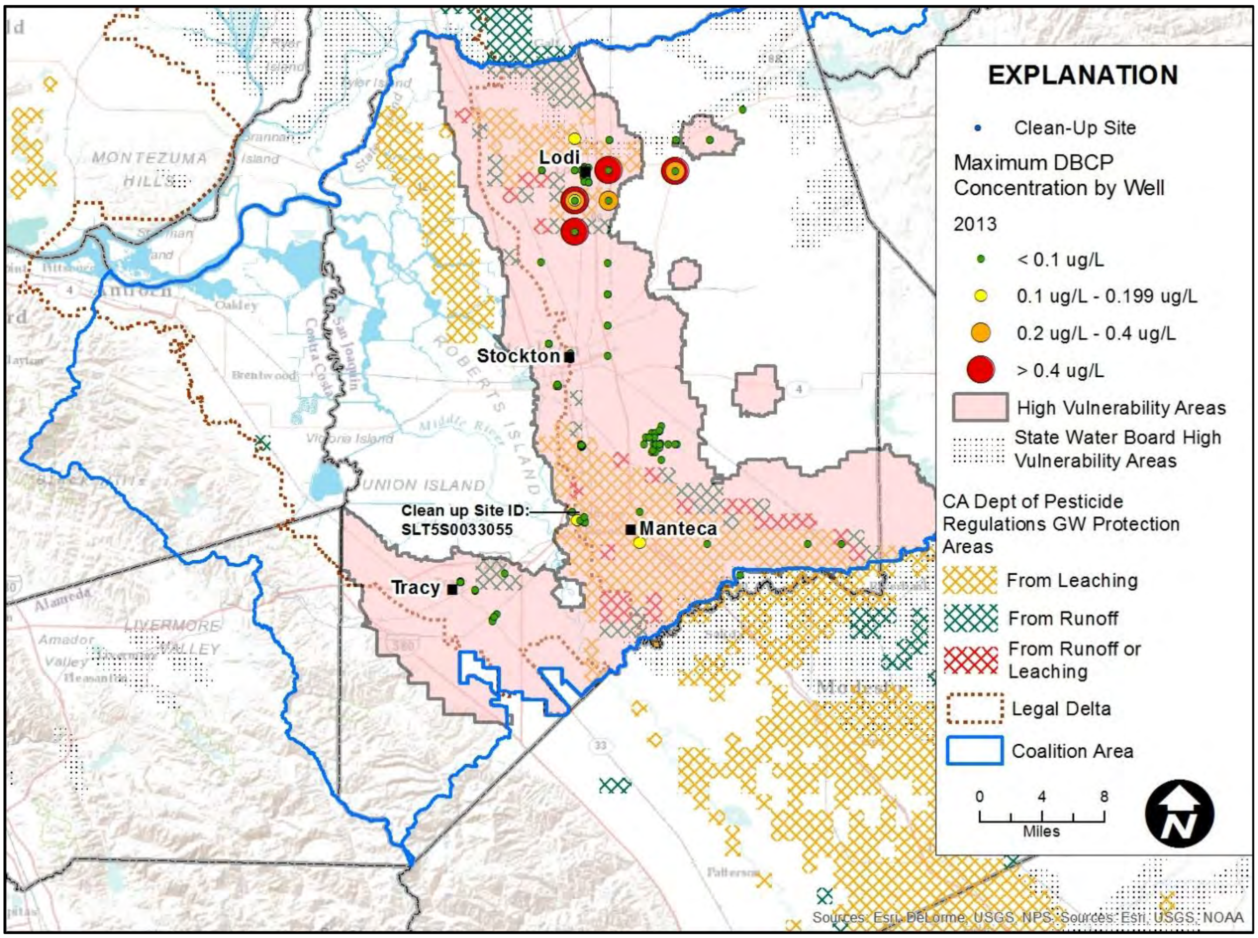

Figure 47. The HVA and maximum 2013 DBCP concentrations.

Figure 48 shows the HVAs overlaid on the public water systems using groundwater. The HVAs overlie almost all of the areas served by public water systems in Stockton, Lodi, Lathrop, Manteca, Ripon, and Tracy.

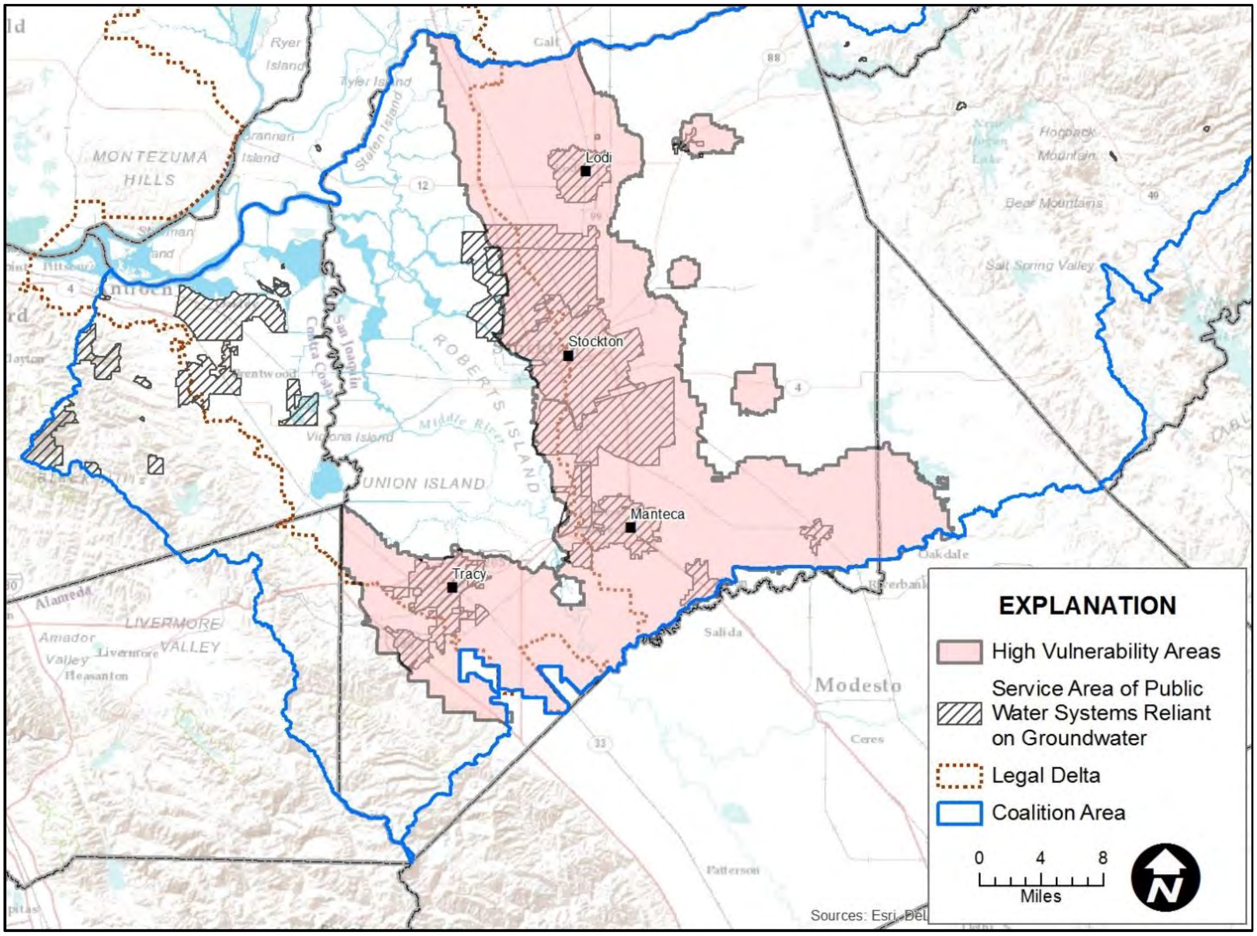

Figure 48. The HVAs and public water systems reliant on groundwater. .

Agricultural land use classes within the HVAs are shown in Table 14. The two agricultural land use classes with the largest area within the HVAs are grain and hay crops (78,200 acres) and deciduous fruits and nuts (77,000 acres). Over 88% of the HVAs are composed of five agricultural land use classes; grain and hay crops (27.6%), deciduous fruits and nuts (27.2%), vineyards (15.9%), pasture (11.1%), and truck, nursery, and berry crops (6.4%).

Proximity to CV-SALTS Basins

We reviewed CV-SALTS documentation and found that the "Salt and Nitrate Sources Pilot Implementation Study" includes nitrate balances for three study areas: Yolo, Modesto, and Tule River.[137] None of the basins being studied lie within the Coalition area.

Table 14. Agricultural land use classes within the HVAs.

Land Use Class	Acres	Percent	Cumulative Percent
Grain and Hay Crops	78,200	27.6%	27.6%
Deciduous Fruits and Nuts	77,000	27.2%	54.9%
Vineyards	44,900	15.9%	70.8%
Pasture	31,300	11.1%	81.8%
Truck, Nursery & Berry crops	18,100	6.4%	88.2%
Idle	16,700	5.9%	94.1%
Field Crops	13,800	4.9%	99.0%
Rice	2,150	0.8%	99.8%
Citrus and subtropical	635	0.2%	100.0%
Total	282,800		

Prioritization within the High Vulnerability Area

We delineated three areas of sequential priority within the HVAs (Figure 49) for prioritization of workplan activities which include conducting monitoring programs and carrying out required studies. As per the MRP, the third-party may prioritize within the HVA based on identified exceedances of water quality objectives for which irrigated agriculture waste discharges are the cause, or a contributing source; the proximity of the HAVs to areas contributing recharge to urban and rural communities where groundwater serves as a significant source of supply; existing field or operational practices identified to be associated with irrigated agriculture waste discharges that are the cause, or a contributing source; the largest acreage commodity types, etc.

Within the Coalition Service Area, three primary criteria were used to delineate the priority areas; the extent and spatial frequency of nitrate exceedances, DRASTIC scores, presence of disadvantaged and disadvantaged unincorporated communities (DACs and DUCs),and land use. Thus, HVA Priority Area 1 includes all identified DUCs within the HVA except one DUC near Tracy and the majority of the DAC area (Figure 49). This priority area contains the largest number and greatest spatial frequency of nitrate exceedances and the largest area of high and medium DRASTIC scores (Figure 50). This priority area also includes the largest contiguous DPR GWPA within the Coalition Service Area (Figure 4). Moreover, Priority Area 1 includes the largest area of groundwater-dependent communities (Stockton, Lathrop,

[137] Larry Walker Associates and others, "Salt and Nitrate Sources Pilot Implementation Study Report," http://www.intpln.com/Docs/Salt%20and%20Nitrate%20Sources%20Pilot%20Implementation%20Study%20Report.pdf. Accessed October 17, 2014.

and Manteca) and their respective particle-tracking-determined contributing areas. The primary non-urban land use within Priority Area 1 is deciduous fruits and nuts (Figure 51).

Within Priority Area 2, the primary non-urban land used is grain and hay (Figure 51). Also, this area contains a large area of DRASTIC high and medium vulnerability areas (Figure 50) and a DUC north of Tracy, which is a groundwater-dependent community. A small area of DACs is included (Figure 49). Priority Area 3 includes the groundwater-dependent communities of Lodi and Lockeford and a relatively small area of medium and high DRASTIC scores and low number of nitrate exceedances. DACs are identified near the Delta but no DUCS have been identified. Vineyards are the primary non-urban land use (Figure 51). This priority area includes a relatively small DPR GWPA (Figure 4).

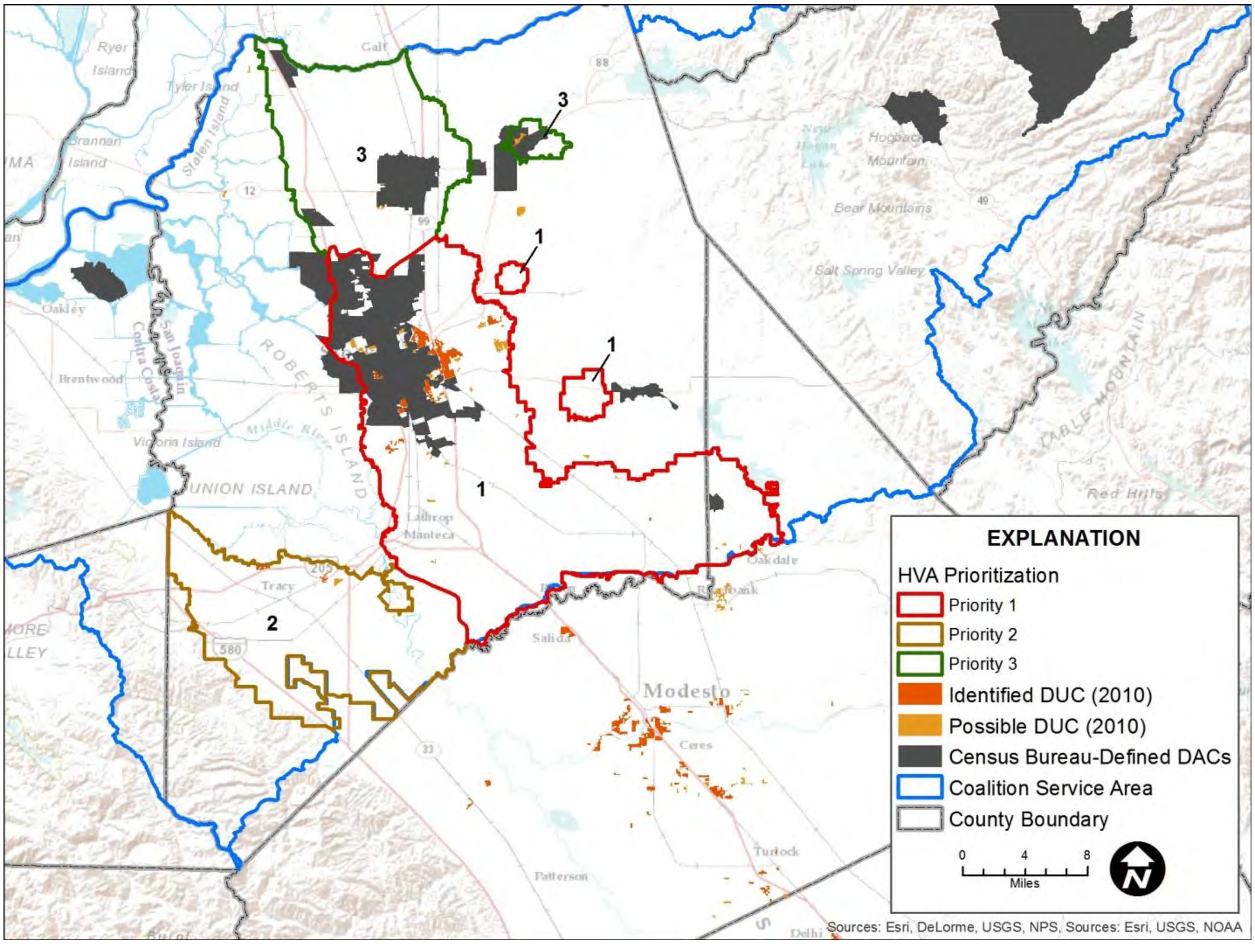

Figure 49. Delineation of priority areas within the HVA and DACS and DUCs.

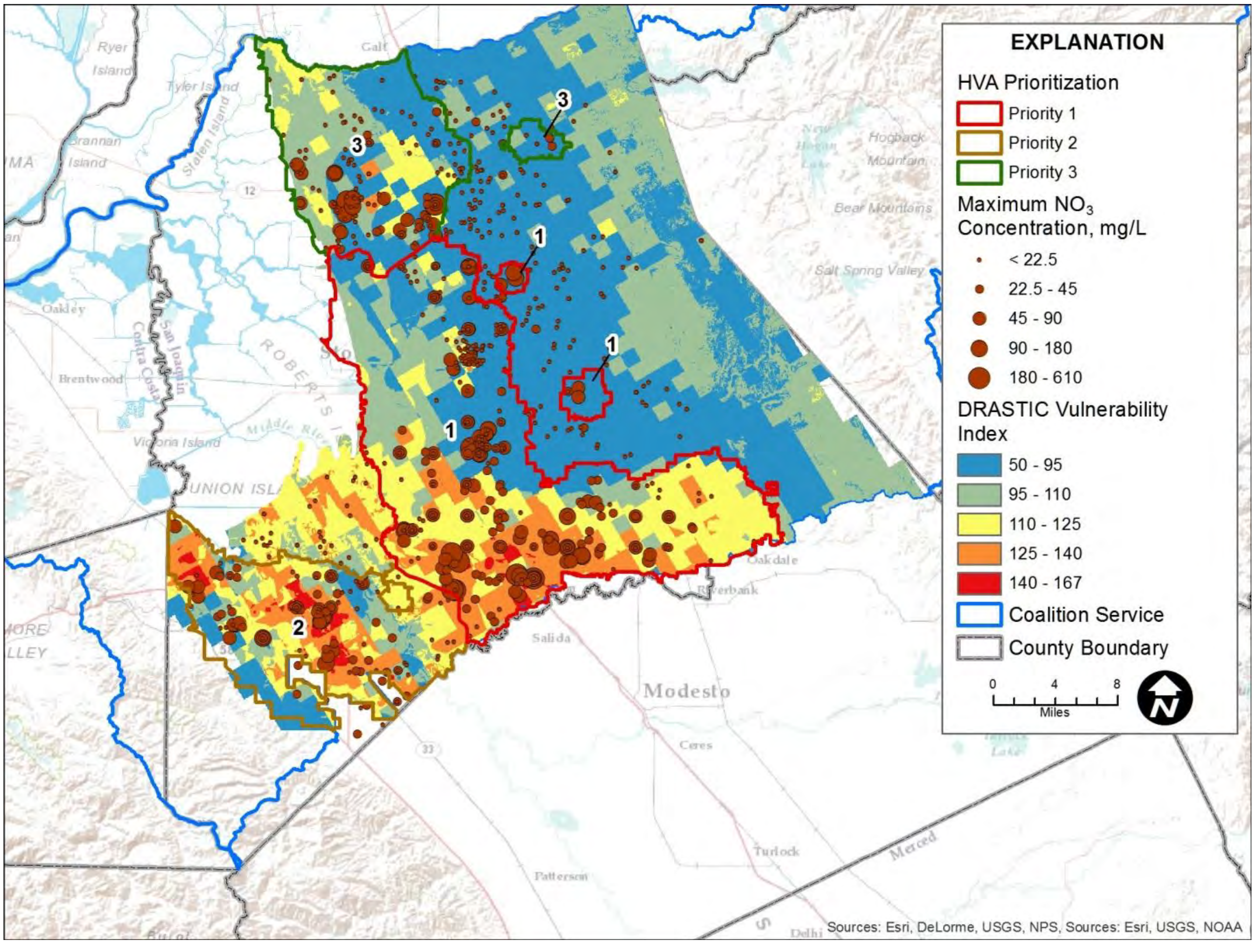

Figure 50. Delineation of priority areas within the HVA, DRASTIC scores and nitrate concentrations.

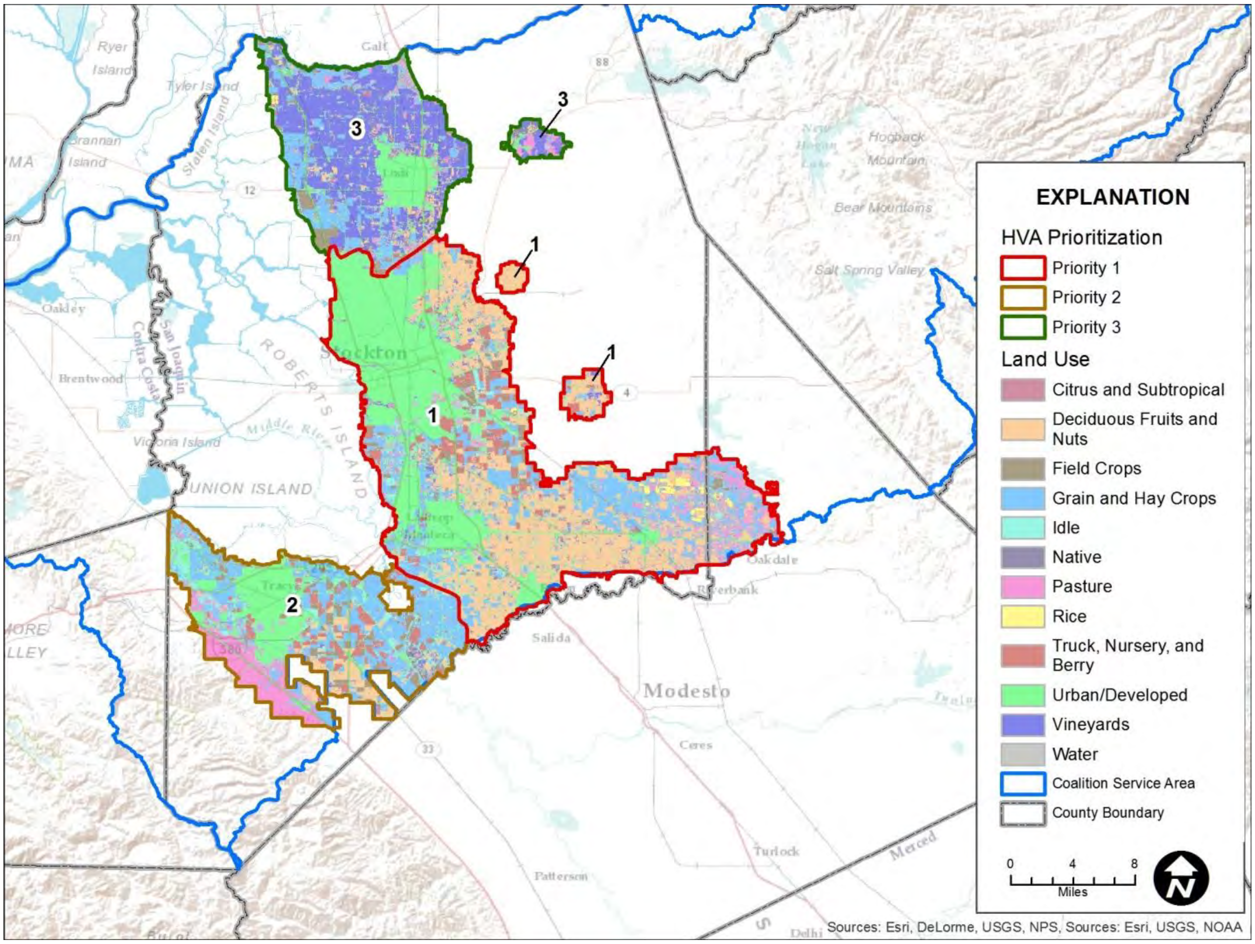

Figure 51. Delineation of priority areas within the HVA and land use.

Sacramento- San Joaquin Delta

The primary objective of data analysis in the Delta was to assess groundwater- surface water interactions and the need for groundwater monitoring in the Delta. The following presents the results of analysis of surface elevations, groundwater levels and groundwater chemical data.

Land-Surface Elevations

Land surface elevations are a key determinant of how water moves from Delta channels to adjacent islands and the need for island drainage. Figure 52 shows the land-surface elevations for the Coalition Service Area within the Legal Delta and the extent of the LIDAR land-surface elevations. Land-surface elevations vary from 12.5 feet above sea level at the eastern (Canal Ranch, Bract, Terminous Tract) southern (Fabian Tract and Union and Roberts islands) and western (southwest of Hotchkiss Tract) edges of the Delta to -20 feet or more in the central Delta.

Groundwater Levels and Artesian Areas

Figure A2 in the Appendix show groundwater hydrographs for data collected throughout the Delta. We used readily available data for the aquifer underlying the organic and fine-grained tidal mud deposits. Visual examination of groundwater hydrographs almost universally indicated temporally stable groundwater elevations from 1989 to 1995. Recent data demonstrate a lack of significant water-level change during the longer term.

In light of the available data that do not show long-term trends and in the general absence of significant hydrogeologic stresses[138] that would cause groundwater levels to change significantly in the Delta during the last 20 years, we deemed it reasonable to estimate groundwater-level averages using the available data for a representative comparison of regional groundwater elevations and delineation of artesian areas which are mapped in Figure 53.

Figure 53 shows that average groundwater elevations varied substantially from a maximum of -0.55 foot on Hotchkiss Tract to minimum of -18.5 feet on Bacon Island. Average groundwater elevations varied spatially independently of surface water levels (Figure 53). Mean stage varied from 3.07 feet in the northern delta to 1.74 feet in the western Delta and 6.32 feet near Bacon Island in the south central Delta (Figure 53).

Artesian conditions are defined by a groundwater elevation above the top of the confined aquifer underneath the tidal peat and muds. In other words, for a well installed and screened in the aquifer underlying the peat, the measured water level would be above the top of that aquifer. We defined the upper elevation of the aquifer as the bottom of the peat which we delineated using methods described

[138] Within the Delta, spatially sparse domestic wells pump from several hundred feet below land surface. Water for irrigation is almost exclusively siphoned or pumped from adjacent channels.

above.

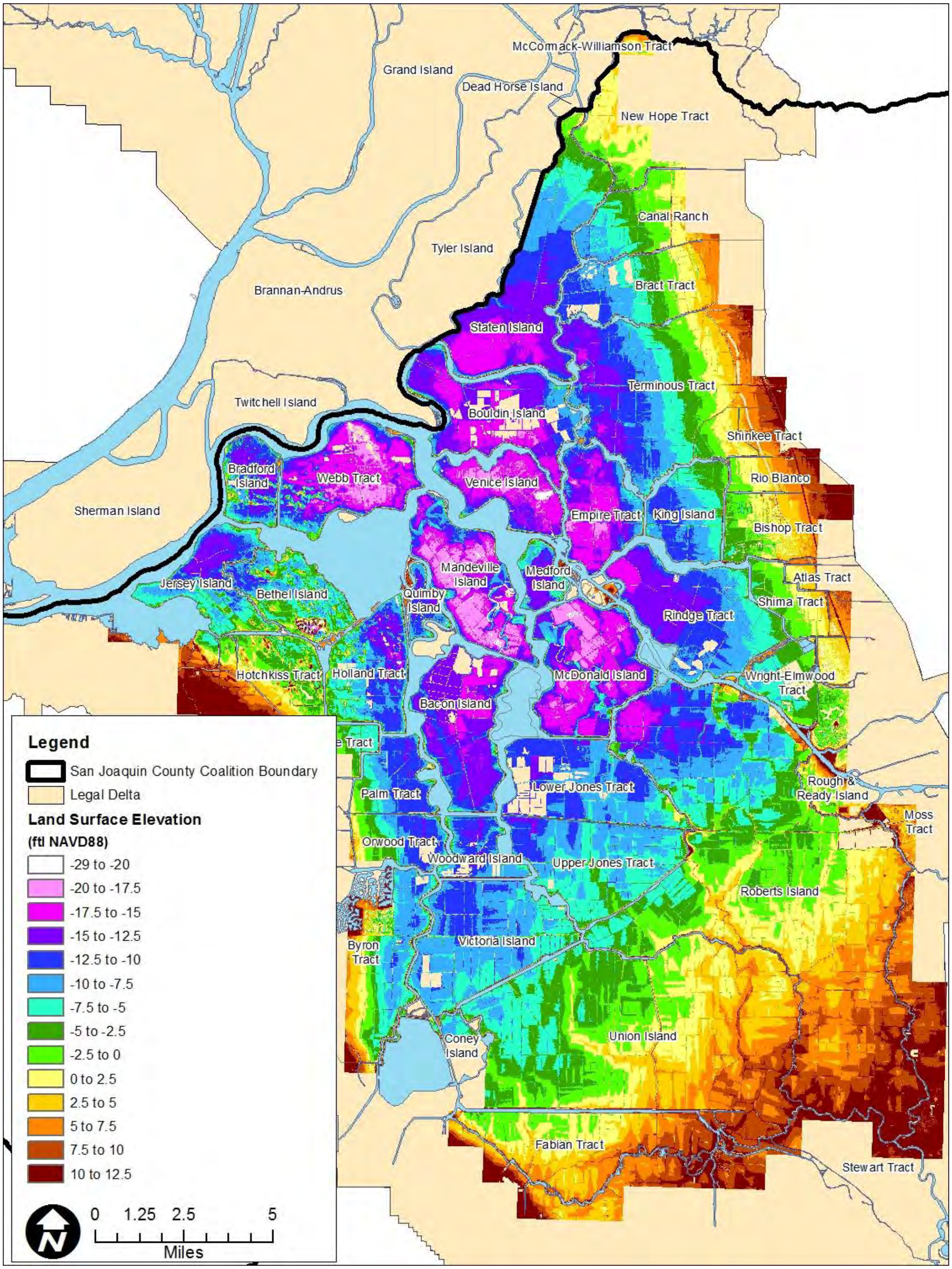

Figure 49. Land surface elevations in the San Joaquin County Delta Coalition Service Area within the Legal Delta.

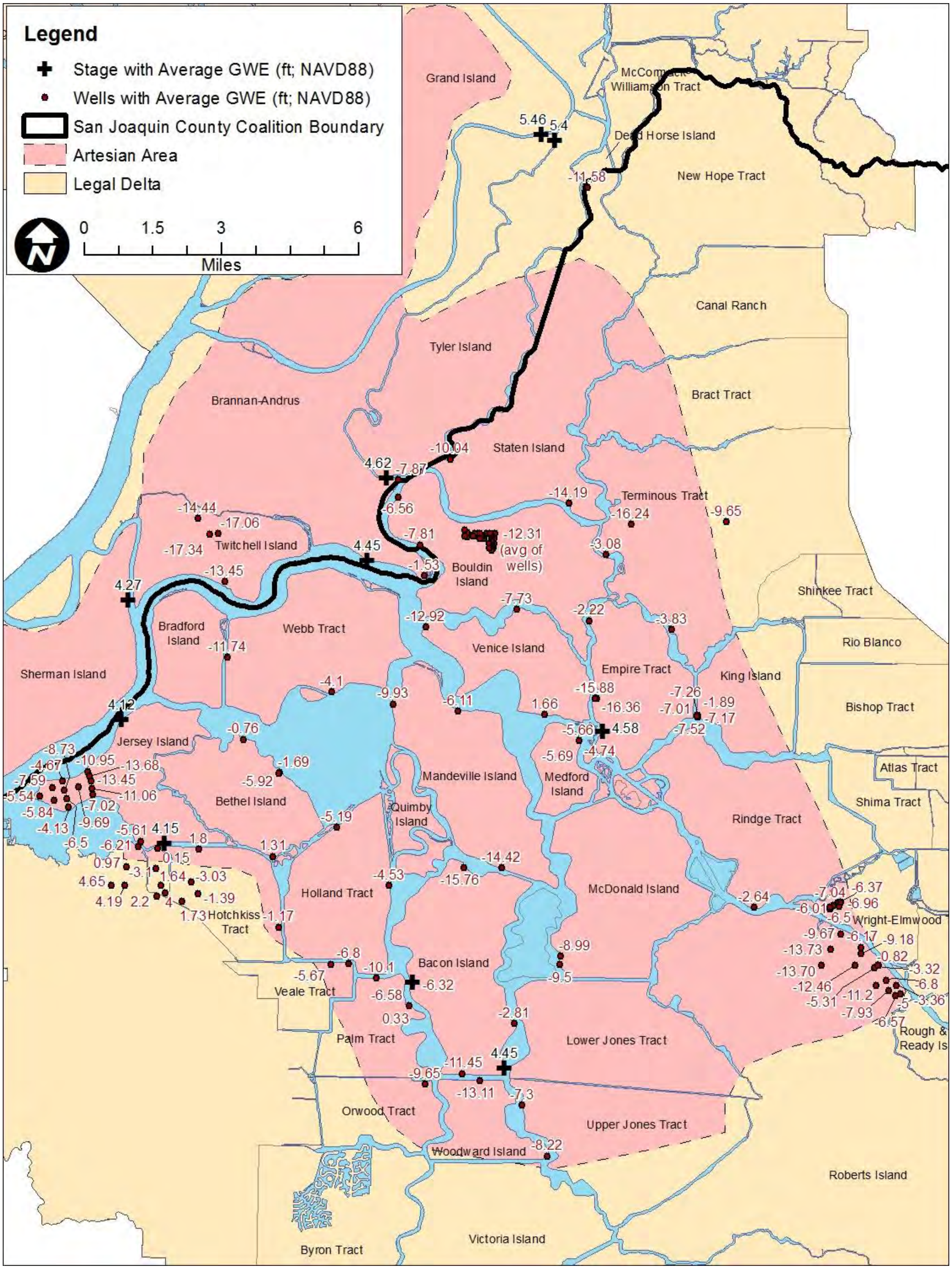

Figure 50. Average groundwater and surface water elevations in the lower aquifer and delineation of artesian areas.

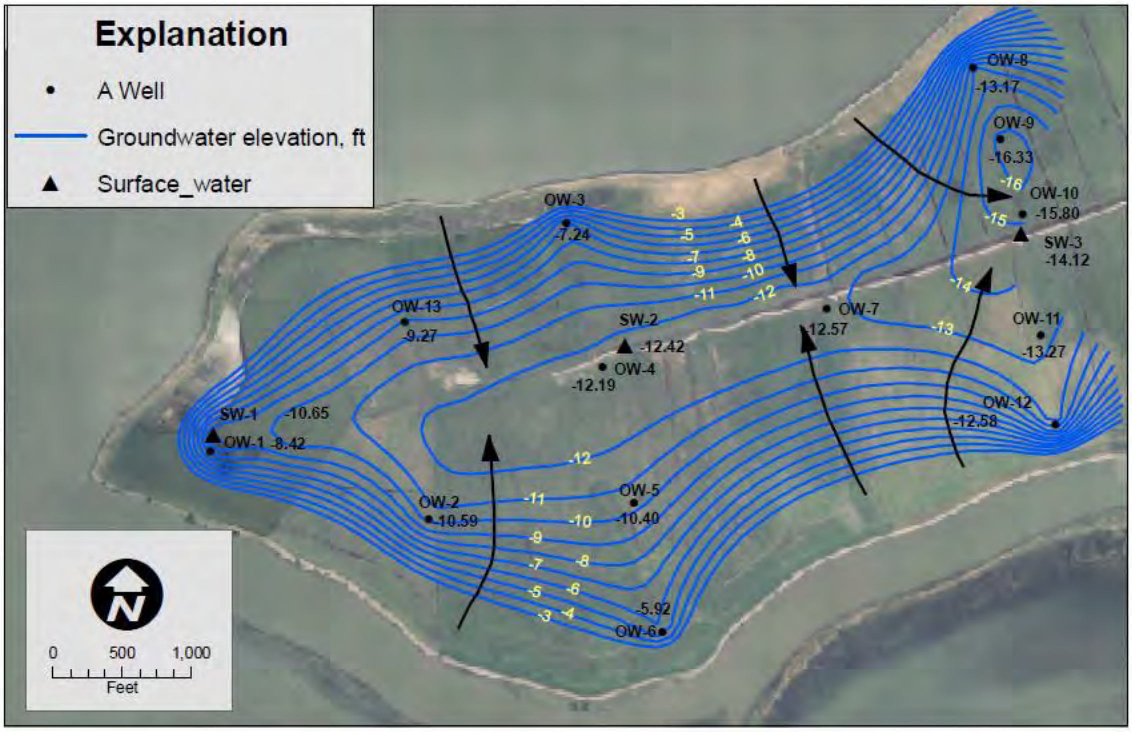

Figure 51a. Groundwater contours and directions of flow based on data collected in shallow wells on Jersey Island. The surface water elevation was 4.5 feet.

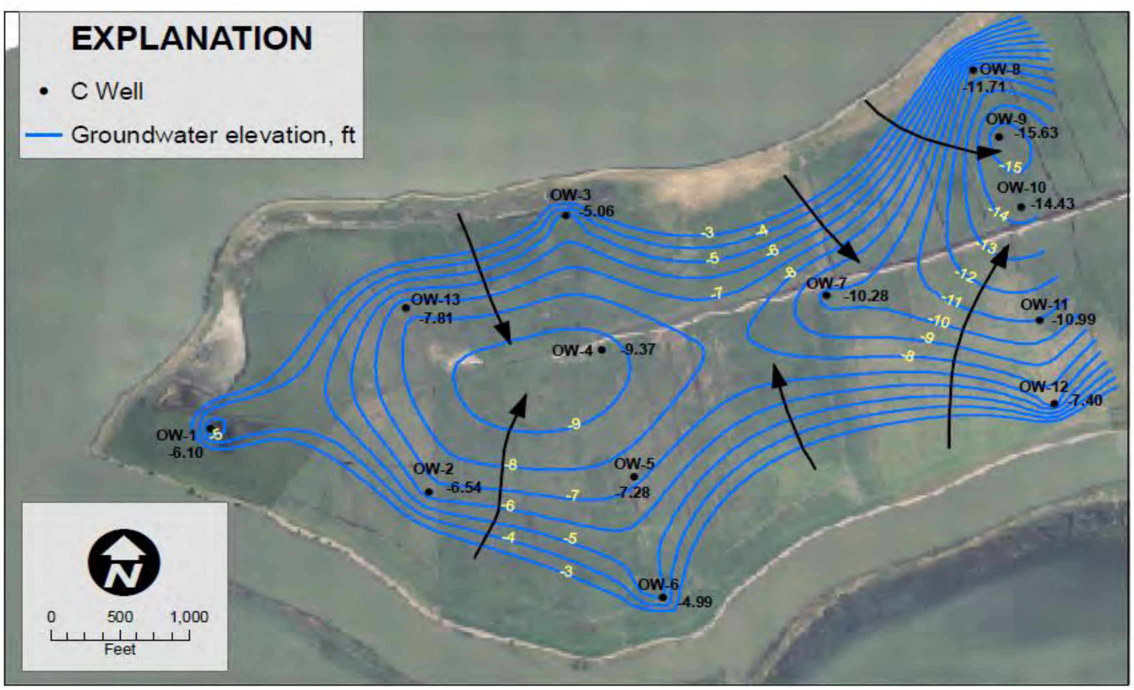

Figure 54b. Groundwater contours and directions of flow based on data collected in deep wells on Jersey Island. The surface water elevation was 4.5 feet.

Deverel and others[139] described the geologic materials underlying the tidal peat and muds as mineral deposits of varied texture deposited during the last glacial period. They observed an approximately 6-inch thick chemically reduced blue clay layer below the peat deposits underlying Twitchell Island. Coarser materials of primarily Sierran origin underlie the clay. We reviewed hundreds of boring logs which show general consistency with this description throughout the Delta within the Coalition Service Area. The texture of this lower confined aquifer underlying the peat is generally a downward coarsening sequence that transitions from clay to silty-sand to fine and coarse sands. Observed variations in groundwater elevations shown in Figure 53 probably reflect the textural differences between the adjacent channel and the well screen. Fine-grained deposits such as silty sand result in greater head loss and lower groundwater elevations relative to coarse-grained deposits such as sand[140].

The available groundwater level data indicate that artesian conditions prevail below land-surface elevations of about –7.5 feet and are present in areas where land-surface elevations range from -2.5 to -5 feet. In the western Delta, groundwater level data from wells in the Dutch Slough area show artesian conditions exist where elevations are lower than -7.5 feet. On Jersey Island, Sherman Island and Twitchell Island, data indicate artesian conditions below - 10 feet. Data on Brannan Andrus and Staten islands and Terminous Tract show artesian conditions where elevations are less than -10 feet. Data for wells on Lower Jones Tract, Woodward Island, Holland and Palm tracts also show artesian conditions below -10 feet. On Wright-Elmwood Tract and Roberts Island, artesian conditions exist where elevations are -2.5 to -5.0 feet.

Artesian areas clearly demonstrate the effect of pressure transmitted from the adjacent channels to the aquifer below the tidal deposits described by Atwater[141] . Upward movement of groundwater to the shallow overlying deposits and drains predominates in these areas. The available data indicate that where artesian conditions exist, they exist near the levees and on the interior of islands.

Specifically, all the wells screened below the peat deposits on Jersey Island show artesian conditions. HydroFocus personnel collected groundwater levels during 2008 and 2009 on the Blind Point area on Jersey Island. In this area of Jersey Island, peat deposits are generally about 10 to 15 feet thick and range from 5 to 19 feet thick. The land surface elevation in this area (see Figure 54) ranges from – 5 to -12 feet. Figure 54 shows the direction of groundwater flow on Jersey Island for shallow wells (Figure 54(a)) that were screened in the peat and deeper wells (Figure 54(b)) that were screened in the mineral deposits underlying the organic deposits on July 31, 2008.

Groundwater flowed from the periphery of Jersey Island to the center of the island where there is a deep drainage ditch (Figure 54). The average surface water elevation surrounding the Blind Point area

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[139] See footnote 30.

[140] Examination of well logs relative to posted groundwater levels in Figure 54 indicate that organic deposits underlain by sand are present where groundwater levels are highest. For example, on Bethel Island, the groundwater elevation is -1.03 foot (BE-12) and sand underlies the peat. Similarly on the Gilbert parcel where the average groundwater level was -2.1 feet, sand underlies peat. Also, on Hotchkiss Tract where the average groundwater level was -0.55 foot (HK-18), sand with silt underlies the organic deposits.
In contrast, where groundwater levels are lower, more fine-grained materials underlie the organic deposits causing greater head loss from the channel to the groundwater well. In the Gilbert-Hotchkiss-Bethel area, lower groundwater levels were measured in the HK-17 Hotchkiss well (-3.51 feet) where silty sand underlies the organic deposits. Also, on Bethel Island where the average groundwater levels were -3.12 and -4.03 feet (BE-11 and BE-19) the organic deposits are underlain by silty sand. Similarly, on Venice Island and Empire Tract where average groundwater levels were -0.64 foot (VN-32) and -4.54 feet (EM-31), sand and silty sand underlie organic deposits, respectively.

[141] Atwater (1982) See footnote 101.

when groundwater measurements were made was 4.5 feet based on gaging station data at Jersey Point and Dutch Slough. Groundwater elevations varied from -5 to -14 feet. Groundwater levels collected during the remainder of the monitoring period showed similar groundwater level elevations and patterns of groundwater flow. Similar conditions were observed in the Dutch Slough area[142]. Groundwater flows from the periphery of the parcels and Jersey Island towards drainage ditches that are below sea level. The land-surface elevation in the Dutch Slough area varies from -6.5 to 12 feet. Similar conditions persist on Twitchell Island[143].

Water Isotopes and Groundwater-Surface Water Interactions

Deverel and others[144] used water isotopes to show that the source of Twitchell Island drain water and groundwater is San Joaquin River water. Specifically, the water isotopic composition of groundwater below 6 feet below ground surface on Twitchell Island was similar to the isotopic composition of San Joaquin River samples collected adjacent to Twitchell Island. Also, isotopic data demonstrated that the San Joaquin River was the source of groundwater and drain water for samples that were partially evaporated due to evaporation of shallow water groundwater.

Isotopic data collected in groundwater samples on islands within the Coalition Service Area show a pattern consistent with Deverel and others[145] (Figure 55). Similar water isotopic relations were observed on Jersey Island, on the Dutch Slough properties, Hotchkiss Tract[146], the Jersey Island Blind Point area and Bouldin Island and Wright-Elmwood Tract[147]. Figure 55 shows that the source of the groundwater for all the sample results is water with similar composition to San Joaquin River as reported by Deverel and others.[148] All points represent groundwater samples.

Most points fall on an evaporative trend line due to varying degrees of evaporation of the groundwater. The origin of the evaporative trend line intersects the meteoric water line close to the location of points representing the San Joaquin River samples reported by Deverel and others[149] thus demonstrating that Delta channels are the source for the partially evaporated water samples. The increased distance that points plot from the intersection of the meteoric water line and the evaporative trend line generally corresponds to greater evaporation. Increased evaporation corresponds to increased salinity.

Points representing samples from deep wells were generally less affected by evaporation and plot closer to the intersection of the evaporative trend and meteoric water lines on Figure 55. These include points representing samples collected from wells from across the Delta on Bouldin Island, Jersey Island and Wright-Elmwood Tract. Groundwater samples were collected from Jersey Island wells screened below 6 feet below land surface and Bouldin Island and Wright Elmwood Tract wells screened below the peat

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[142] HydroFocus, Inc. 2013. Dutch Slough Restoration Area Third and Fourth Quarters 2012 Annual Groundwater Monitoring Report prepared for Department of Water Resources.
[143] Deverel and others 2007, See footnote 30.
[144] ibid
[145] ibid
[146] HydroFocus, Inc. 2013. Dutch Slough Restoration Area Third and Fourth Quarters 2012 Annual Groundwater Monitoring Report prepared for Department of Water Resources, footnote 94.
[147] Bachand and Associates, HydroFocus, Inc., University of California, Davis, U.S. Geological Survey, Duck Unlimited, Contra Costa Water District. 2006. Reducing Non-point DOC and Nitrogen Exports from Rice Fields: A Pilot Study and Quantitative Survey to Determine the Effects of Different Hydrologic Management Practices, Report submitted to the Central Valley Regional Water Quality Control Board, SWRCB Agreement No. 03-165-555-0.
[148] see footnote 30.
[149] see footnote 30.

deposits. This demonstrates that Delta channel water is the source of the groundwater in these wells. Points representing samples collected from shallow wells on Jersey Island, Wright-Elmwood Tract and Bouldin Island wells screened in the peat deposits show definitive evidence of evaporation of shallow groundwater and plot further from the origin on the evaporative trend line.

Points representing Dutch Slough samples also show varying degrees of evaporation. These samples were collected from wells screened below 20 feet on the Gilbert, Emerson and Burroughs parcels and Hotchkiss Tract. This area is mostly outside the area of artesian wells however, drainage ditches collect shallow groundwater and discharge to adjacent sloughs. Points representing wells on the Ironhouse Sanitary District Mainland (ISD Mainland) also demonstrate evidence of shallow groundwater evaporation.

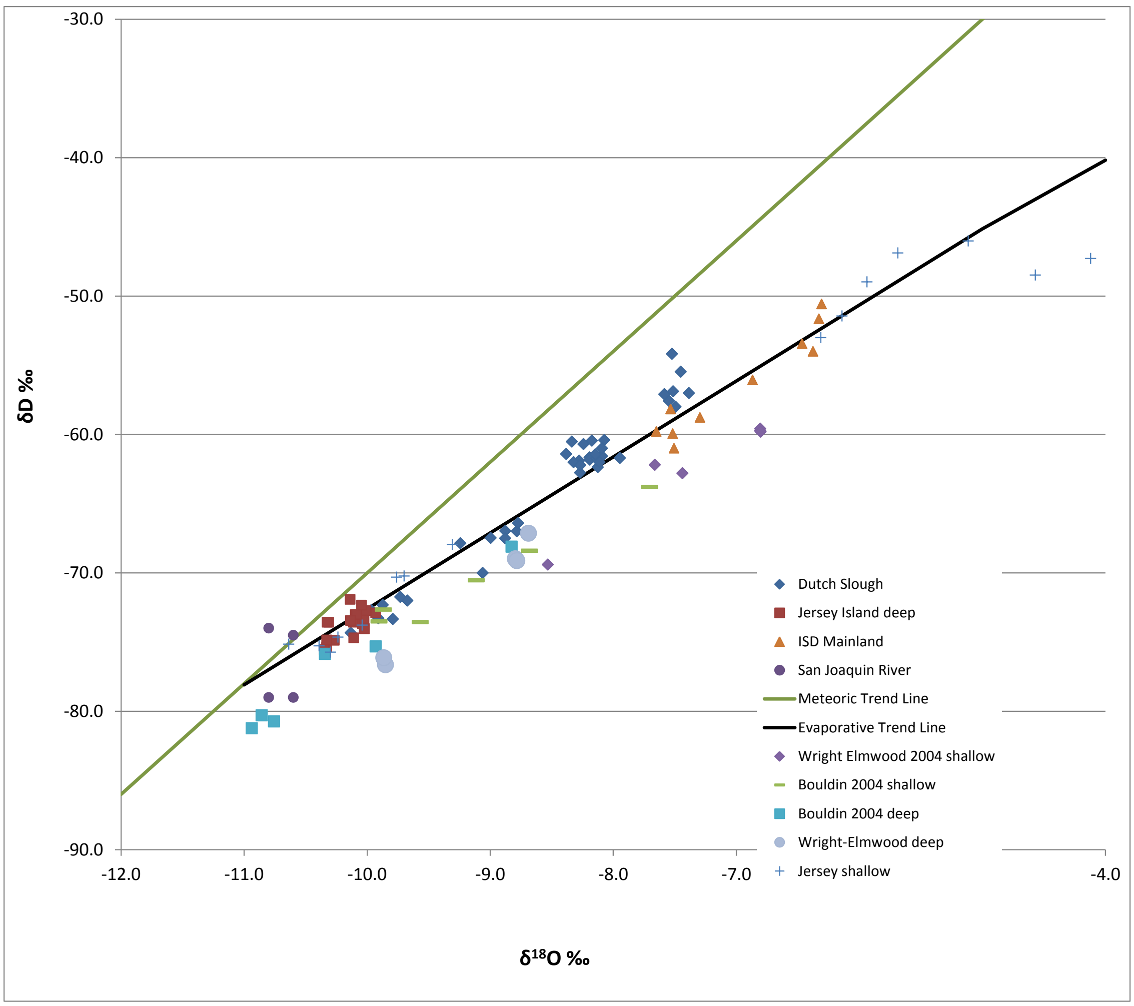

Figure 52. Isotopic composition of groundwater samples collected on the Dutch Slough properties, Jersey Island, Hotchkiss Tract, Bouldin and Wright-Elmwood Tract.

Discussion

Non-Delta

Our objectives were to develop a delineation of areas of high vulnerability to groundwater quality impacts related to agriculture and to assess groundwater-surface water interactions in the Sacramento-San Joaquin Delta for determination of need of groundwater monitoring and to assess vulnerability. In addition and consistent with GAR objective defined in the WDR, we sought to provide an assessment of all readily available, applicable, and relevant data and information to determine the high vulnerability areas where discharges from irrigated lands may result in groundwater quality degradation

The draft Order stated that the GAR shall include detailed land use information, information regarding depth to groundwater, groundwater recharge information, soil survey information, groundwater constituent concentrations (potential constituents of concern include any material applied as part of the agricultural operation) and information about existing groundwater data collection and analysis efforts. We have gathered, organized and analyzed these data and used them to understand the factors that affect nitrate concentrations in groundwater.

Ultimately, the GAR will establish priorities for implementation of monitoring and studies within high vulnerability or data gap areas and provide a mechanism for review of the HVAs. It will also provide a basis: 1) for assessing groundwater quality trends, 2) evaluating the effectiveness of agricultural management practices to protect groundwater quality and 3) for establishing groundwater quality management plans. Specifically, the GAR will be used to:

- Establish priorities for implementation of monitoring and studies within high vulnerability or data gap areas;
- Assess groundwater quality trends and identify monitoring wells for trend monitoring;
- Evaluate the effectiveness of agricultural management practices to protect groundwater quality;
- Establish groundwater quality management plans.

Thus we delineated 3 areas descending priority within the HVA.

Groundwater Nitrate Concentrations in Non-Delta Areas

Mapping of nitrate concentrations generally indicate an increasing number of high concentrations and exceedances with time since the 1970s. However, the number of well samples collected per year has also increased with time. Exceedances of the MCL are generally associated with wells shallower than 250 feet and areas where the depth to groundwater is within 100 feet of land surface. From 2009 – 2013, wells in agricultural areas with average nitrate concentrations at or above the MCL are located primarily in the northern (near Lodi) and southwestern (near Manteca) part of the Coalition Service Area, southern Delta and southwest of the Delta near Tracy. Northeast of Stockton, southeast of Lodi northeast of Stockton and southeast of Lodi and southeast of Tracy, localized high groundwater nitrate concentrations lie outside of the DPR GWPA. Nowhere within the Coalition Service Area, do areas of high nitrate concentrations coincide with State Water Board Hydrogeologically Vulnerable Area.

The effect of depth to groundwater, well construction and depth is consistent with other studies of groundwater quality in agricultural areas. For example, Canter[150] and Hallberg and Keeney[151]described

[150] Canter, L.W. 1996, Nitrates in groundwater, Lewis Publishers.

the inverse relation between depth to groundwater and well depth and nitrate concentrations. Deeper wells and depth to groundwater primarily allow for processes that reduce nitrate concentrations such as dilution and chemical reduction to occur to a greater extent than for shallow wells and where there is a shallow water table. Barbash and Resek[152] summarized the effects of well construction and depth on pesticide concentrations in agricultural areas. While these authors described the topic of the effect of well construction as controversial, they also presented substantial evidence to point to improperly constructed wells (by current standards) as a factor resulting in pesticides in groundwater. Their analysis established that well depth was unequivocally and inversely proportional to herbicide concentrations.

Nitrate concentrations were positively and significantly correlated with salinity (total dissolved solids, conductivity) and salinity-related variables. These included (correlation coefficients are in parentheses) conductivity (0.42), hardness (0.93), total dissolved solids (0.64), calcium (0.69), magnesium (0.66), sodium (0.43), chloride (0.50) and sulfate (0.60). Since groundwater salinity generally increases with increasing proximity to the San Joaquin River where groundwater levels are shallowest, the higher nitrate concentrations are likely more the result of the shallow water levels which are spatially associated with the higher salinities.

Using multiple linear regression analysis, we determined that the potential explanatory factors such land use and crop, recharge, soil and subsurface texture, recharge explain a small percentage of the spatial variability in nitrate concentrations. We found a general lack of significant differences for groundwater nitrate concentrations by land use in agricultural areas. However, our analysis indicates that groundwater nitrate concentrations associated with deciduous fruits and nuts were significantly greater than nitrate concentrations associated with truck and field crops, idle agricultural lands, pastures, and vineyard at the 95% confidence level.

Our regression model for estimating the spatial variability in groundwater nitrate concentrations missed the mark in several areas. The inability of the regression analysis to effectively predict all areas of high nitrate concentrations, to explain a substantial portion of the variance in nitrate concentrations, or indicate significant explanatory factors or processes, led us to conclude that groundwater nitrate concentrations can be treated for purposes of mapping HVAs as randomly distributed. We therefore used non-parametric geostatistical methods (indicator kriging) to delineate vulnerability areas.

Indicator kriging has been used in multiple locations internationally to estimate groundwater quality vulnerability areas. We used indicator kriging in combination with determination of groundwater contributing areas to public water systems and disadvantaged communities to initially delineate HVAs that encompass all areas where groundwater nitrate concentrations are over the MCL, there are increasing nitrate concentrations in agricultural areas and encompass almost all of the area where groundwater nitrate concentrations are above one-half the MCL. The land use class with the largest area within the HVAs is deciduous fruits and nuts (60,865 acres). Over 87% of the HVAs are composed of five land use classes; deciduous fruits and nuts, pasture, field crops, grain and hay crops and truck, nursery, and berry crops.

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[151] Hallberg, G.R. and Keeney, D.R., 1993, Nitrate in (Alley, W.M., ed.) Regional Groundwater Quality, Van Nosgrand Reinhold, New York.

[152] Barbash, J. E. and Resek, E. A, 1996, Pesticides in Groundwater, Distribution, Trends and Governing Factors, Ann Arbor Press.

To further delineate areas highly vulnerable to groundwater nitrate exceedances, we used ArcGIS Spatial Analyst to develop a system to evaluate and delineate areas with varying potential for groundwater contamination using the DRASTIC methodology. The DRASTIC results were used to supplement the indicator kriging and particle tracking results by providing an indication of areas that are susceptible to groundwater degradation where no groundwater nitrate concentration exceedances have been identified. Because of the association of nitrate exceedances with areas with moderate scores, we extended the HVA to include those moderately scored areas outside the Delta as well as the contributing areas delineated by the particle tracking and the DPR GWPA north of Lodi.

Groundwater Monitoring

Five primary existing groundwater quality data collection efforts described previously, DPR, DPH, USGS, CDWR, and San Joaquin County Flood Control and Water Conservation District, provide useful data for the Coalition. For nitrate, DPH will continue to provide the most data for drinking water supply wells. USGS efforts will depend on external funding and are not likely to be continuous. San Joaquin County Flood Control and Water Conservation District has monitored and published groundwater levels in over 550 wells but little groundwater quality data. For future monitoring of groundwater quality within Coalition Service Area, this network will likely serve as a good source of wells for collection of samples[153].

Sacramento-San Joaquin Delta

Physical and isotopic data support the applicability of the conceptual model proposed by Deverel and others[154] (Figure 3) for much of the Sacramento-San Joaquin Delta within the Coalition Service Area within the Legal Delta (Figure 2).

Subsurface lithology, groundwater levels, artesian areas and flow to drainage ditches

Examination of well and boring logs and analysis of groundwater level data from throughout the area demonstrates similar hydrogeologic conditions where elevations are below sea level. Specifically, water flows from adjacent channels into island groundwater systems and discharges to networks of island drainage ditches.

The available groundwater level data shows that within the area below sea level, measured groundwater levels are below sea level and average channel water level elevations. Even in areas where the land is above sea level, there is movement of surface water onto land such as the Ironhouse Sanitary District Mainland property. This is illustrated by the Dutch Slough data. Artesian conditions prevail throughout the Delta where land-surface elevations are generally lower than -7 feet (29% of the Delta Coalition Service Area) but also are present where elevations are within -2.5 feet. There is thus upward flow from underlying mineral aquifers into organic and/or tidal deposits. Surface water in adjacent channels is connected to this mineral aquifer that underlies the organic deposits and is the driving force for the artesian hydraulic head on Delta islands. Therefore, irrigation water percolating through agricultural soils does not flow downward to supply wells but laterally to drainage ditches.

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[153] Conversations with San Joaquin County personnel indicate a willingness to cooperate with the Coalition in the development of a groundwater quality monitoring network.

[154] Deverel and others, 2007 See footnote 30.

Flow from adjacent channels onto Delta islands necessitates drainage and discharge of drainage water. Networks of drainage ditches collect primarily groundwater which originated from adjacent channels via seepage or siphoned irrigation water. During irrigation events which last a few days, surface runoff typically discharges to drainage ditches. Drainage ditches are the key hydrologic features that result in upward movement of groundwater where land surface elevations are below or close to sea level. The local hydraulic gradients and depths of drainage ditches determine the depth of capture of groundwater. Deep flow paths, which originate below the depth of the ditches, intersect to the ditches. We employed the following equation to estimate the effective depth of groundwater captured by drainage ditches[155].

For drainage conditions similar to Twitchell Island, we estimated an effective depth of 25 feet. Therefore, for islands and tracts where land surface is close to or slightly above sea level and below the channel water surface elevation, groundwater at depths of about 25 feet below drainage ditches will be captured by drainage ditches.

$$\mathbf{D} = [(2\mathbf{WH})/(\pi\mathbf{GR})]^{1/2} \qquad (1)$$

where:,

D is the effective depth of capture below the drainage ditch bottom, in feet;
W is the width of the ditch (about 10 feet);
H is the water level difference between the aquifer and ditch, about 2 feet;
G is the regional hydraulic gradient (about 0.001); and,
R is the ratio between horizontal and vertical hydraulic conductivity (10).

The average surface-water elevation in the south-central Delta adjacent to Lower Jones Tract and Bacon Island is 4.45 feet. Moreover, land surface elevations range from 2.5 to 5 feet on southern Fabian Tract, eastern Union Island and southern Roberts Island. Therefore, in light of the depth of capture calculation above, drainage ditches in these areas where the surface water elevation is above or near land surface elevation, drains will capture groundwater that flows upwards from substantial depths.[156]

Water Isotopes Data and Surface-Groundwater Interactions

Available water isotope data are consistent with physical data. For areas in Coalition Service Area where land-surface elevations range from 0 to -17.5 feet, groundwater samples are derived from Delta channel water. Deep groundwater samples collected below the peat deposits generally have isotopic compositions similar to the composition of Delta channel water samples. Shallower samples show evidence of varying degrees of partial evaporation and points representing these samples fall on an evaporative trend line that intersects the meteoric water line near where points representing Delta channel water.

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[155] Zheng, C., H. F. Wang, M.P. Anderson, and K. R. Bradbury, 1988, “Analysis of interceptor ditches for control of groundwater pollution”, Journal of Hydrology, vol. 98, pp. 67-81.

[156] Consistently, Deverel and Fio used geochemical data and analysis and groundwater flow modeling to demonstrate similar capture depths in the western San Joaquin Valley. See Deverel, S.J. and Fio, J.L., 1991, Groundwater flow and solute movement to drain laterals, western San Joaquin Valley, California. I. Geochemical assessment, Water Resources Research, 27, 2233 – 2246 and Fio, J.L. and Deverel, S.J., 1991, Groundwater flow and solute movement to drain laterals, western San Joaquin Valley, California, II. Quantitative hydrologic assessment, Water Resources Research, 27, 2247 - 2257.

Consistently, on Jersey Island, the Central Valley Regional Water Quality Control Board allowed monitoring of drainage ditches instead of groundwater. On Jersey Island, Ironhouse Sanitary District discharges treated wastewater on agricultural fields on the western area of the islands where land-surface elevations range from -5 to -7.5 feet. Consistent with the conceptual model of groundwater flowing to drainage ditches, the Central Valley Regional Water Quality Control Board in WDRs for Order 5-01-237 required that the Discharger (Ironhouse Sanitary District) on Jersey Island monitor surface water in the dewatering ditches "in lieu of shallow groundwater". As is the case with almost all Delta islands, Jersey Island is dewatered to maintain groundwater at a depth approximately 2 to 4-feet below the ground surface. Nine surface water (drainage ditches) sampling locations exist on Jersey Island.

Groundwater on Delta islands where land surface is below surface water elevations flows to networks of drainage ditches from a substantial depth below the bottom of the drainage ditch. This was demonstrated by the use of equation 1. This upward flowing groundwater can be chemically and hydrologically represented by drainage water samples. The chemical composition of drainage water varies seasonally and with management practices. On Twitchell Island during May through November, deep groundwater flowed to drainage ditches which determined the drain-water chemical composition. During December through April, shallow water from the variable saturated zone dominated drain flow and this resulted in a different chemical composition.

During irrigation events, drainage ditches generally receive irrigation runoff. Also, island main drains serve as temporal-spatial integrators of processes that occur within the island drainage network. Therefore, island main drains serve as temporal-spatial integrators of processes that occur within the island drainage network.

We delineated the area in the Sacramento-San Joaquin Delta within the Coalition Service Area where the Deverel and others conceptual model applies based on the available physical and chemical evidence presented here (Figure 56). The data indicate that where land-surface elevations are about 5 feet or lower, there is groundwater flow onto islands and drainage ditches collect groundwater from substantial depths. This area where the conceptual model applies extends to McCormack-Williamson in the north and central and eastern portions of Canal Ranch Tract, Bract Tract, Terminous Tract, Shinkee Tract, Rio Blanco Tract, Shima Tract, and Wright Elmwood Tract in the east. The southeast portions on Fabian Tract, Union Island and Robert's Island also lie within this applicability area. The western boundary transects include Hotchkiss, Veale, Orwood, Veale and Byron tracts. Consistent with upward flowing groundwater, nitrate concentrations in well samples collected within this area are less than 22.5 mg/L. In the development of groundwater vulnerability areas, we excluded this area of upward flowing groundwater. Groundwater nitrate exceedances were absent in the area where there is upward flowing groundwater and drainage ditch water can be used to characterize shallow groundwater quality (Figure 56).

Based on data and literature (e.g. Deverel and others[157]) two factors contribute to low nitrate concentrations in Delta wells. Chemically reducing concentrations result in denitrification and upward flowing groundwater moves nitrate and other constituents of concern to drainage ditches. Other nitrogen species present in chemically reducing conditions such as ammonia have been detected in shallow groundwater which flows to drainage systems. Due to lack of water quality concerns related to agricultural activities as demonstrated by the available data and the processes affecting groundwater

[157] Deverel, Steven J., David A. Leighton and Mark R. Finlay. 2007. See footnote 30.

flow, we delineated the area within the Legal Delta and the Coalition Service Area shown in Figure 56 as low vulnerability for groundwater quality related to irrigated agriculture.

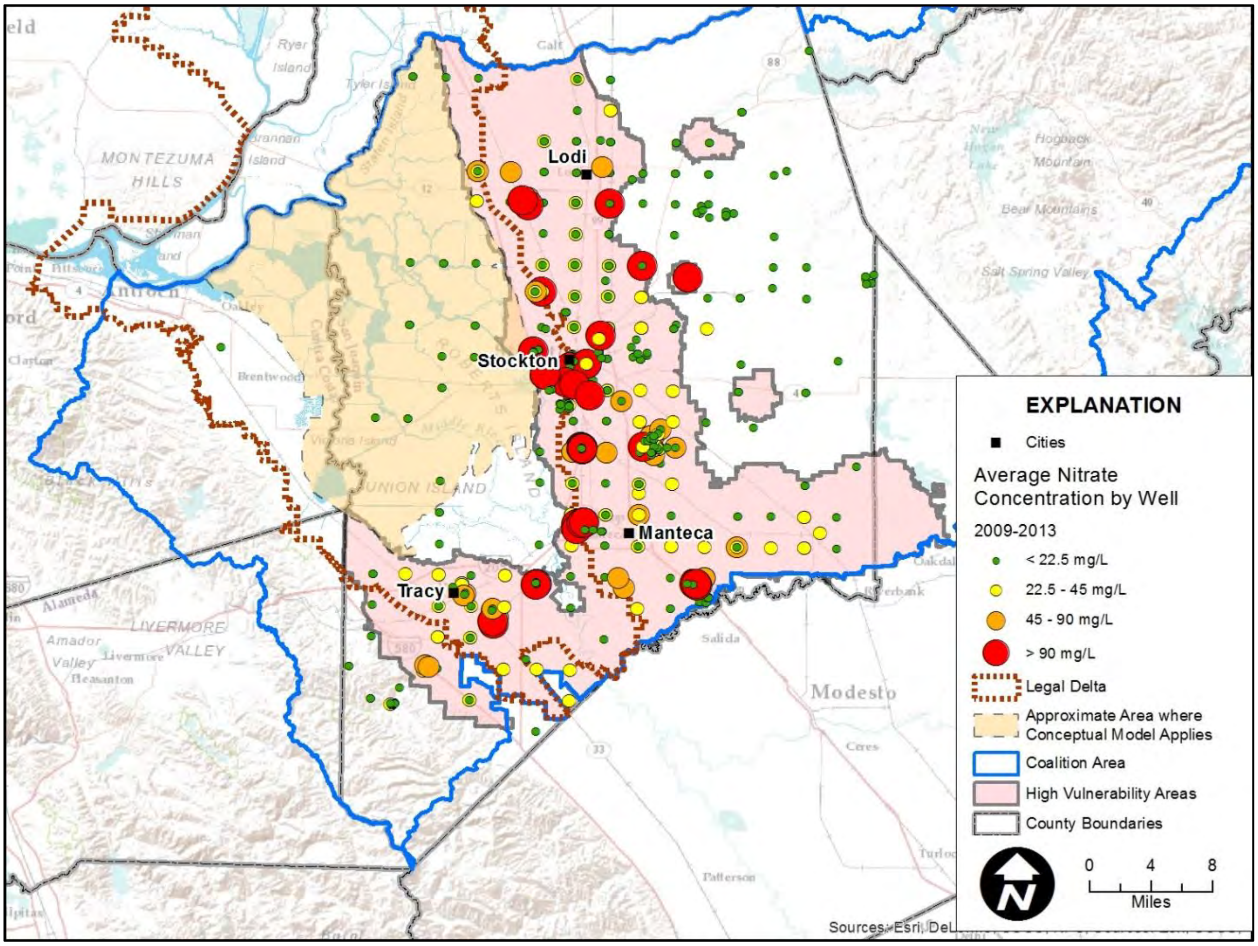

Figure 53. Areas where the conceptual model presented by Deverel and others for upward flowing groundwater is generally applicable.

Summary and Conclusions

Non-Delta

In the Non-Delta area of the Coalition Service Area, we gathered, organized, mapped and analyzed water quality data and relevant geographic data. We used these data and analyses to attempt delineate areas where groundwater is vulnerable to nitrate exceedances. However, this approach did not yield a satisfactory delineation of vulnerability areas. Instead, we used a geostatistical approach for delineation of vulnerability areas. Key conclusions follow.

- The frequency of nitrate concentrations exceeding the MCL generally increased with time from the 1970s to 2013.
- Nitrate exceedances were most prevalent immediately east of the Delta and where groundwater levels were less than 100 feet below land surface.
- Nitrate concentrations in exceedance of the MCL were also predominantly in wells shallower than 250 feet. Our interpretation of the major-ion data in relation to nitrate concentrations is consistent. Low nitrate concentrations are associated with appears to be more geochemically evolved, deeper groundwater.
- Statistical analysis indicates a general lack of significant differences for groundwater nitrate concentrations by land use in agricultural areas. However, our analysis indicates that groundwater nitrate concentrations associated with deciduous fruits and nuts were significantly greater than nitrate concentrations associated with truck and field crops, idle agricultural lands, pastures, and vineyard at the 95% confidence level.
- Particle tracking with the Central Valley groundwater flow model indicated that public water system wells extract a mixture of local water table recharge and deeper groundwater. The water table recharge occurs in areas slightly up-gradient 2 miles or less, and the deeper groundwater is recharge that enters the groundwater system further distances away.
- We experimented with regression of maximum nitrate concentrations (dependent variable) with recharge, depth to water, fertilizer application rate, subsurface texture, and soil texture (independent variables). We performed multiple linear regression using combinations of 3-5 independent variables. All regression models explained a relatively small percentage of the nitrate variance; the maximum R^2 was 6.2%. All regression relations were significant at the 95% confidence level.
  - Due to the inability of the regression model to satisfactorily predict areas of high nitrate concentrations, we concluded that groundwater nitrate concentrations can be treated for purposes of mapping vulnerability areas as randomly distributed.
- We concluded that mapping the spatial variability for initial delineation of vulnerability areas was more effectively accomplished using indicator kriging in combination of the groundwater contributing areas such that all agricultural areas where nitrate concentrations have exceeded the MCL are encompassed. Wells with statistically significantly increasing nitrate concentrations in agricultural areas were also encompassed.
- We further used the DRASTIC model to delineate areas of intrinsic vulnerability due to hydrogeologic and topographic factors.
- High vulnerability areas which encompass an area of 392,400 acres (20% of the total Coalition Service Area) were delineated where nitrate concentrations were over the MCL

and groundwater contributed to urban areas served by groundwater south and east of the Delta. We delineated the Delta as low vulnerability.

- The two land use classes with the largest area within the high vulnerability area are grain and hay crops (78,200 acres) and deciduous fruits and nuts (77,000 acres). Over 88% of the high vulnerability areas are composed of five land use classes; grain and hay crops (27.6%), deciduous fruits and nuts (27.2%), vineyards (15.9%), pasture (11.1%), and truck, nursery, and berry crops (6.4%).
- Within the HVAs, we developed three priorities for prioritization of workplan activities. Three primary criteria were used to delineate the priority areas; the extent and spatial frequency of nitrate exceedances, DRASTIC scores, presence of disadvantaged and disadvantaged unincorporated communities (DACs and DUCs),and land use.

Delta

We utilized available relevant physical and chemical data to assess the validity of the conceptual model for groundwater, drain water and surface water presented by Deverel and others (2007)[158] for the portion of the Coalition Service Area within the Legal Delta. We utilized available relevant physical and chemical data to assess the validity of the conceptual model for groundwater, drain water and surface water presented by Deverel and others (2007)[159] for the portion of the Coalition Service Area within the Legal Delta. This model states that groundwater flows from adjacent to channels to drainage ditches and that drainage water is representative of the processes occurring in island groundwater. Groundwater flow to drainage ditches is slow, occurring during years to decades. The following bullets summarize the results of our analysis.

- Physical and isotopic data generally support the applicability of the conceptual model proposed by Deverel and others (2007)[160] for about 55% of the Sacramento-San Joaquin Delta within the Coalition Service Area where land-surface elevation is at or below sea level.
- Physical evidence included lithology and groundwater level data which provided 1) evidence that artesian conditions prevail throughout the central Delta and/or flow from adjacent channels to island groundwater systems and 2) similar subsurface geologic conditions throughout the Coalition Service Area within the Delta.
- Isotope data for groundwater samples collected on islands in the Coalition Service Area and Twitchell Island demonstrate that:
    - Groundwater is derived from adjacent channels;
    - Shallow groundwater is subject to evaporation;
    - Drainage ditches collect partially evaporated and non-evaporated groundwater and;
    - Drainage-water quality varies seasonally.
- Drainage ditches and main drains on Delta islands serve as collectors of groundwater and spatial and temporal integrators of processes affecting groundwater quality and can be used to monitor shallow groundwater quality.
- Based on the readily available data, the area where the Deverel and others (2007)[161] model is applicable includes Tyler and Staten islands in the north and most of New Hope Tract, Canal Ranch, Bract Tract, Terminous Tract, Shinkee Tract, Rio Branco Tract, Bishop Tract, Shima Tract, and Wright Elmwood Tract in the east. The most of Fabian Tract, Union Island and Robert's

[158] See footnote 30.
[159] ibid
[160] ibid
[161] ibid

Island are included in the south. The western boundary transects Hotchkiss, Veale and Byron Tract.

- Due to the lack of evidence for groundwater quality concerns related to agriculture and the hydrologic processes affecting groundwater flow and quality, i.e. upward flow to drainage systems, we deemed the Legal Delta portion of Coalition Service Area as low vulnerability for groundwater quality impacts related to irrigated agriculture.