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Sent: Wednesday, February 1, 2017 11:18 AM
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Cc: Kemper, Lauri@Waterboards; Copeland, Patrice@Waterboards; Tucker, Robert@Waterboards; Coony, Mike@Waterboards
Subject: LAMP Meeting Follow-up

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Subject: LAMP Meeting Follow-up

Jason and Joshua – The main two topics we discussed on Thursday 01-26-17 were:

1. Additional justification for continuation of ½ acre lot sizes for single family homes at 1 Equivalent Dwelling Unit (EDU)/acre or 250 gal/acre/day.

2. Additional clarification of Water Quality Assessment Program elements.

In regard to Item # 1 – The County should understand that the border line where density becomes “high density” is not the current Basin Plan density of essentially ½ acre, but instead the Tier 1 conservative densities (see attached). For desert areas with low rainfall, the minimum density is 2½ acres per equivalent dwelling unit. We ask for the county to provide justification that the proposed LAMP density is protective of groundwater and/or surface water quality. These justifications may include, but not be limited to, the following.

- Number of buildable lots (smaller is less impact),
- Location of buildable lots (deeper water means impacts are observed in longer time frame),
- Robustness of the monitoring program (earlier warning of potential impact allows time to take corrective action), or
- Foreseeable actions (where sewers are planned in reasonable timeframe, continued buildout may be smaller impact.

In regard to Item #2 - The County could improve the Water Quality Assessment Program (WQAP) outline by using the LAMP considerations in OWTS Policy section 9.1 (described below). As examples, the WQAP could include, but not be limited to commitments for:

- Identify and map areas of high domestic well usage, such as Soap Mine area of Barstow;

- Identify and map areas of high OWTS density, such as in Wrightwood.

- Identify areas where geological features affect transport of septic tank effluent, such as fractured bedrock, poorly drained soils, shallow soils, and high groundwater, from available information and percolation report knowledge.

- Identify assessment tools that may be used in a predictive manner, such as the USGS model ,or similar vadose zone model to determine the flux of septic tank effluent to groundwater. The USGS paper was for the Yucca Valley area (See attached). USGS has offered use of the UZ model for other areas that have similar climate and geology as Yucca Valley. One of the findings in this paper is that OWTS nitrate discharges reached groundwater in ½ the time from areas of high density OWTS than in areas with lower density. We recommend that the county consider partnering with other local agencies to assess the occurrence of groundwater recharge from OWTS discharges in the higher density areas. Lahontan Water Board staff suggests that this computer modeling be conducted in conjunction with the 5-Year WQAP report and periodically thereafter when comparing the computer model results to other collected groundwater data as a result of land development and growth patterns. The scope and cost of model use is dependent upon the nature of work proposed. The USGS contact person for use of the model is Claudia Faunt, Program Manager, 619-225-6142 ccfaunt@usgs.gov.

- Identify specific work and collaboration efforts, or needs, with other agencies to split the costs of a WQAP. For instance, the County can work with city/town jurisdictional agencies with LAMPs so as to develop a WQAP that meets the needs of both the county and the jurisdictional agency. This may include the Mojave Water Agency, Crestline Sanitation District, and others.

- Identify specific areas where possible future dedicated groundwater monitoring wells may be necessary to supplement predictive assessment conclusions. This may include the Wrightwood area. Note: You were going to send me the monitoring well destruction report for that well. Unfortunately, that public infrastructure investment is lost. In the future, groundwater monitoring wells should not be hastily destroyed if they can be converted to additional uses, such as collecting groundwater elevation or water quality data than originally intended.

- Identify key domestic well partners that agree to collect, or allow data to be collected, from their wells in areas where high OWTS density exists, or expected.

- Identify tools for conducting the assessment, including data storage and retrieval, supplemental mapping and technical analysis.

The OWTS Policy section 9.1 considerations are the following:

1. Degree of vulnerability to pollution from OWTS due to hydrogeological conditions.

2. High Quality waters or other environmental conditions requiring enhanced protection from the effects of OWTS.

3. Shallow soils requiring a dispersal system installation that is closer to ground surface than is standard.

4. OWTS is located in area with high domestic well usage.

5. Dispersal system is located in an area with fractured bedrock.

6. Dispersal system is located in an area with poorly drained soils.

7. Surface water is vulnerable to pollution from OWTS.

8. Surface water within the watershed is listed as impaired for nitrogen or pathogens.

9. OWTS is located within an area of high OWTS density.

10. A parcel's size and its susceptibility to hydraulic mounding, organic or nitrogen loading, and whether there is sufficient area for OWTS expansion in case of failure.

11. Geographic areas that are known to have multiple, existing OWTS predating any adopted standards of design and construction including cesspools.

12. Geographic areas that are known to have multiple, existing OWTS located within either the pertinent setbacks listed in Section 7.5 of this Policy, or a setback that the local agencies finds is appropriate for that area.

Regards – Jay

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Attachments:
Predicting Groundwater Nitrate-Nitrogen Impacts - Hantzsche - Finnemore.pdf
Storage and mob natural and septic NO3 in thick unsat zones - Izbicki 20.pdf

Predicting Ground-Water Nitrate-Nitrogen Impacts

by Norman N. Hantzsche[a] and E. John Finnemore[b]

Abstract

The buildup of nitrates in upper ground-water zones is a potential cumulative effect of on-site sewage disposal practices which is not addressed by standard siting and design criteria. Literature concerning the contribution and fate of nitrogen beneath septic tank disposal fields is reviewed. From these findings, convenient, simplified methods are developed for estimating long-term ground-water nitrate increases on an area-wide basis. The methods are presented in a manner useful to engineers, planners, and regulatory agencies for routine evaluation of existing and proposed land developments and for design of large, common disposal systems. Typical solutions are shown graphically to illustrate the relative importance of various factors, including development density, rainfall recharge, and soil denitrification. Predicted values are compared with actual monitoring data for three California communities to verify the reasonableness of the suggested methods. Several possible regulatory applications are suggested.

Introduction

The use of on-site subsurface sewage disposal systems, in particular septic tank disposal fields, has long been recognized as one of the most effective means of dealing with domestic waste-water problems in rural settings. Many soils have a high capacity to accept, filter, and assimilate sewage effluent. Also, in sparsely populated areas, the availability of large amounts of open land tends to minimize possible water quality or public health effects associated with such sewage disposal practices. There is now, however, a growing trend to make permanent use of on-site systems for large-scale urban fringe, rural residential, and recreational developments. Small, unsewered communities are also tending more and more to maintain and continue with the use of septic tanks rather than embarking on major sewerage construction projects.

During the past several years, water quality and public health agencies and researchers throughout the country have worked to develop guidelines and criteria to improve on-site sewage disposal practices. The aim has been to minimize potential health and water quality problems associated with the siting, design, construction, and maintenance of such systems. The main concern is the protection of water supplies and general public health from the standpoint of bacterial contamination and disease transmission. Protection of ground-water quality, for example, is achieved by requiring a specified vertical separation distance between the disposal system and the highest expected rise of the water table. This provides an unsaturated soil zone wherein high degrees of physical, biological, and chemical treatment occur. Surface waters are similarly protected by the establishment of lateral setback requirements.

An important water quality issue that previously has not been addressed in guidelines and regulations is that of the persistent or increasing effect of large numbers of systems in concentrated areas. For example, many substances contained in sewage are soluble and may move relatively unaffected through the soil to accumulate in underlying ground waters or discharge to adjacent surface waters. Also, under certain conditions, the total volume of sewage discharged from many systems may alter local ground-water levels to the point of affecting the performance of individual systems or the degree of treatment provided by the soil system (Finnemore and Hantzsche, 1983).

The buildup of nitrate in ground water is potentially one of the most significant long-term consequences of on-

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site sewage disposal practices. With each new proposal for development there is a growing need to quantify and evaluate possible changes in ground-water quality that may result. What are most needed are convenient and reliable analytical tools that can be used by regulatory agencies, engineers, and others to make assessments early in the planning process.

Nitrogen Contributions and Transformations

Nitrogen is present in high concentrations in septic tank effluent primarily as ammonium-nitrogen (75-80%), with organic nitrogen making up the remainder (Otis et al., 1975). Total nitrogen concentrations in such effluent have been reported to vary from 25 mg/l to as much as 100 mg/l, the average generally being in the range of 35 to 45 mg/l (U.S. EPA, 1980). Walker et al. (1973a) estimated the typical annual nitrogen contribution from a family of four to be about 33 kg. For a residential lot size of 0.25 acres, this nitrogen contribution would be more than 200 times the amount that would typically be introduced naturally from mineralization of soil organic nitrogen and precipitation.

Upon introduction into the soil through subsurface disposal fields, nitrogen may undergo various transformations, the most important being nitrification and denitrification.

Nitrification may be broadly defined as the biological conversion of nitrogen in organic or inorganic compounds from a reduced to a more oxidized state (Alexander, 1965). The predominant end product is nitrate (NO_3^-) because it is a stable anionic species. This also explains its high degree of mobility in the soil. Virtually complete nitrification of ammonium-nitrogen has been found to occur in the unsaturated zone in well-aerated soil below septic tank disposal fields (Walker et al., 1973b). The resulting nitrate may then pass easily through the soil along with percolating effluent and other recharge waters. Immobilization of NO_3^- by plants or through microbial uptake into biomass may occur to a limited extent, but these are generally considered to be insignificant NO_3^- sinks (Alexander, 1965; Lance, 1972), and thus largely ineffective in reducing the amount of NO_3^- available for percolation to ground water.

Denitrification refers to the biological or chemical reduction of nitrate and nitrite to volatile gases, usually nitrous oxide and molecular nitrogen or both (Broadbent and Clark, 1967). It is the only mechanism in the soil that can effect significant reduction of nitrate in percolating effluent (Alexander, 1965; Lance, 1972). The most favorable soil conditions for denitrification are (a) the abundance of organic carbon sustrate, (b) high soil moisture content, and (c) high soil pH (Broadbent and Clark, 1967; NAS, 1978). The rate of denitrification appears to be independent of nitrate concentration over a fairly wide range (Broadbent and Clark, 1967).

Most nitrogen balance studies of fertilizer application have indicated a large nitrogen deficit attributable to denitrification. Losses range from 1 to 75 percent of the applied nitrogen, but are typically between 10 and 25 percent (Broadbent and Clark, 1967). These rates of denitrification are generally considered to also apply to waste waters disposed of to land, although, according to the EPA, no thorough nitrogen-balance studies have been reported which either substantiate or refute this assertion (U.S. EPA, 1981). One of the few detailed studies of nitrogen beneath septic tank disposal fields is the work of Walker et al. (1973a, 1973b). This work found denitrification to be an insignificant nitrate removal mechanism in unsaturated sandy soils, as deep as 15 to 20 feet, due to the lack of anaerobic conditions and organic material which support denitrifying bacteria. It was thus suggested that the only active mechanism of lowering the nitrate content in such situations is dilution by higher quality ground water or by recharge waters.

Simplified Prediction of Ground-Water Nitrate Buildup

In the long-term, water quality in the upper saturated zone is closely approximated by the quality of percolating recharge waters. This is the critical ground-water zone in which potential nitrate impacts are likely to be most strongly expressed. A simplified prediction of the nitrate impacts of on-site sewage disposal systems over a defined geographical area can thus be made by constructing a mass balance, considering only inputs from waste water and recharge of rainfall (also meant to include snowmelt) and losses due to denitrification in the soil column and the upper portion of the aquifer.

The expression for the resultant average concentration, n_r, of nitrate-nitrogen in recharge water is given by

$$n_r = \frac{I n_w (1 - d) + R n_b}{(I + R)} \quad (1)$$

in which I = volume rate of waste water entering the soil averaged over the gross developed area, in inches per year; n_w = total nitrogen concentration of waste water, in milligrams per liter; d = fraction of nitrate-nitrogen loss due to denitrification in the soil; R = average recharge rate of rainfall, in inches per year; and n_b = background nitrate-nitrogen concentration of rainfall recharge at the water table, exclusive of waste-water influences, in milligrams per liter.

In this expression, the value of n_r is computed simply as the weighted average nitrate-nitrogen concentration of percolating rainfall and waste water, adjusted for expected losses due to soil denitrification. A critical simplifying assumption in equation (1) is that there is uniform and complete mixing of waste water and percolating rainfall over the entire developed area, and that this is completed at the water table. This assumption is made to allow calculation of a predicted mean nitrate-nitrogen concentration for the area as a whole. In reality, such complete, uniform mixing would not be expected to occur because of the irregular spatial and temporal distribution of waste-water loading and rainfall recharge. Nevertheless, the predicted value should correspond with the mean concentration in the ground water determined from representative sampling.

Full conversion of nitrogen to nitrate is also assumed in equation (1). This is a reasonable assumption in most cases.

The approximation of nitrate concentrations obtained from equation (1) also ignores dispersion, lateral flow, and mixing with ground-water flow from upgradient areas. These processes would generally contribute to additional reduction of nitrate-nitrogen concentrations in ground water to the extent that the nitrate-nitrogen concentration of ground-water flow from upgradient areas is lower. Equation (1) thus provides a conservative (worst case) first approximation of ground-water nitrate-nitrogen concentration resulting from the combined effect of on-site sewage disposal systems and precipitation. This is for estimation of long-term effects (i.e., over years) on ground-water quality, and is not intended for prediction of seasonal changes.

A common land use planning dilemma is that of determining acceptable development densities, sometimes referred to as the carrying capacity of the land. From the standpoint of ground-water nitrate-nitrogen impacts, the critical minimum gross acreage per developed lot, A, may be defined as that which would result in a value of n_r equal to 10 mg/l, the commonly accepted drinking-water limit. By setting $I = 0.01344\ W/A$ and $n_r = 10$ mg/l, and then rearranging equation (1), A is then given by

$$A = \frac{0.01344W[n_w - dn_w - 10]}{R(10 - n_b)} \qquad (2)$$

in which A is expressed in terms of gross acres/dwelling unit (DU); W is the average daily waste-water flow per dwelling unit, in gallons; and 0.01344 is a conversion factor having units acre inch day DU yr^{-1} gal^{-1}.

Typical Solutions

Solution of the foregoing equations requires input data for several disposal system and site variables, all of which can have a significant effect on the predicted nitrate-nitrogen concentration. Graphical solutions are presented here for typical ranges of these variables, as an aid in selecting appropriate values, and in identifying situations of potential concern.

The predicted resultant average ground-water nitrate-nitrogen concentration, n_r, computed from equation (1) is plotted for convenience in Figure 1 against the fraction of waste-water recharge, I, relative to rainfall recharge, R, for a selected range of values for soil denitrification, d, and waste-water nitrogen loading, n_w. Background nitrate-nitrogen loading, n_b, typically falls in the range of 0.5 to 1.0 mg/l, and is assumed here to be 1.0 mg/l. Exceptions to this would be if the area has large numbers of confined livestock or significant expanses of fertilized crops or turf areas (e.g., parks), which would tend to increase background nitrate-nitrogen loadings above the typical values suggested here. The results plotted in Figure 1 show a wide range of potential effects, highly sensitive to the initial selection of values for n_w and d. Two curves are plotted for the average value of $n_w = 40$ mg/l, with denitrification rates of 0 and 0.25, respectively. The typical range is represented on the high and low sides by the curves for (a) $n_w = 50$ mg/l, $d = 0$ and (b) $n_w = 30$ mg/l, $d = 0.25$. The curve for $n_w = 40$ mg/l and $d = 0.25$ would be considered the most representative of typical on-site sewage disposal situations (U.S. EPA, 1980; 1981). In addition to proper selection of values of n_w and d, the importance of

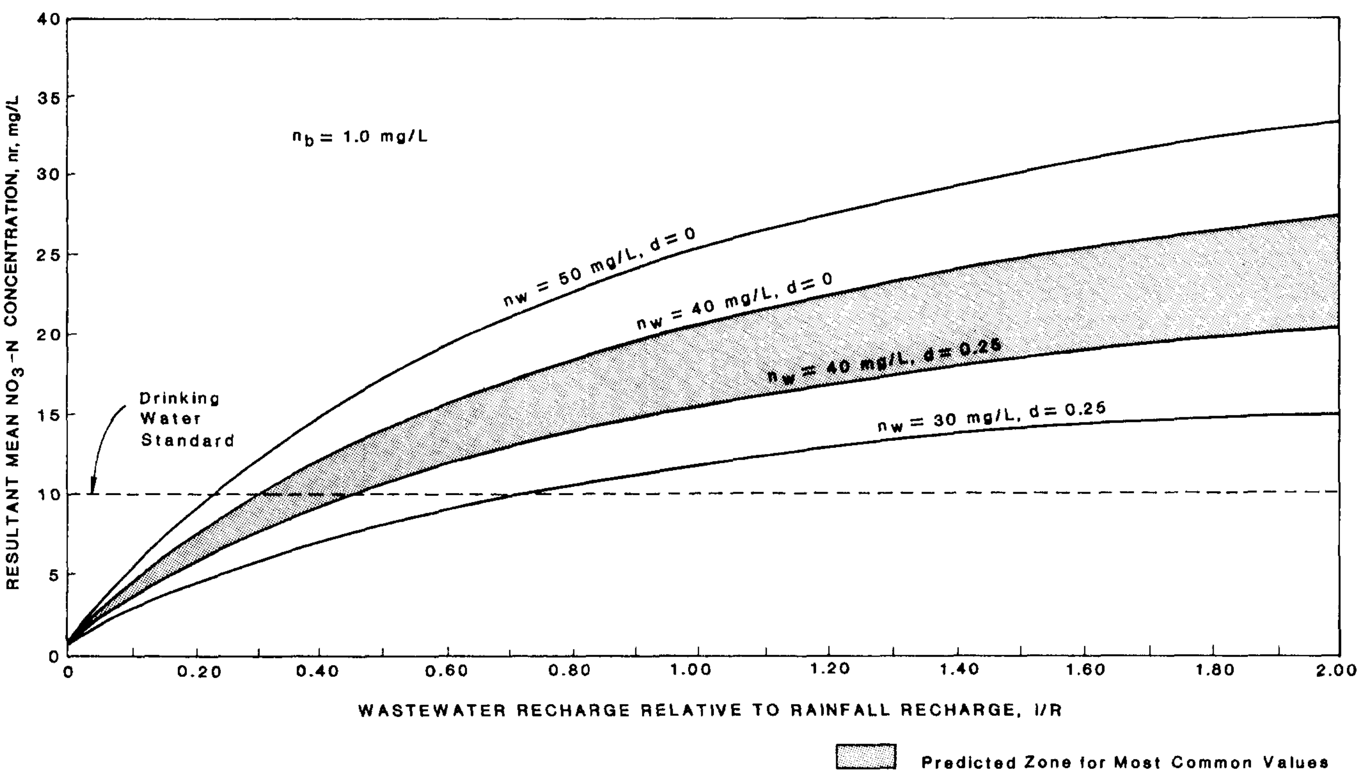

Fig. 1. Resultant ground-water nitrate-nitrogen concentration as a function of effluent quality, denitrification, and I/R.

accurately estimating the quantity of recharge waters is clearly evident, particularly in cases of higher nitrogen loading and lower denitrification rates.

In Figure 2, the critical minimum gross acreage per lot, A, is plotted against the annual rate of rainfall recharge, R, for a selected range of values for n_w and d, with $n_b = 1.0$ mg/l as before. In this instance the long-term waste-water flow, W, is assumed equal to 150 gal/day per DU, on the basis of an average expected occupancy of three persons per residence and 50 gal/person/day. The U.S. EPA (1980) cites 45 gal/day as the typical per capita flow for residential dwellings. The influence of climate and the water balance is seen to be significant, particularly for lower ranges of R, i.e., drier climates. Thus, in desert areas, very large lots may be necessary.

In typical new developments of single family residences, practical lot size limits exist because of minimum space requirements for site development, disposal fields, roadways, open space, etc. These limits may be on the order of 0.25 to 1.0 gross acres per dwelling unit, depending on local codes and specific development plans. As seen in Figure 2, such practical or statutory limits may often be more stringent than the critical minimum gross acreage per lot, A, determined from equation (2). This is particularly true as R values increase.

Case Study Examples

To demonstrate and test their validity, the preceding methods for assessing nitrate impacts were compared against the actual ground-water quality data for three California communities. All three of these communities rely on individual on-site systems for sewage disposal. In each case ground-water contamination by nitrates has been documented by extensive monitoring programs. The three communities reviewed here as case study examples are: (1) the Bolinas Mesa area in Marin County; (2) the Chico area in Butte County; and (3) the Baywood-Los Osos area in San Luis Obispo County (Figure 3).

Description of Study Areas

The general physical characteristics of the three study areas are summarized in Table 1. Background on the study sites is discussed below.

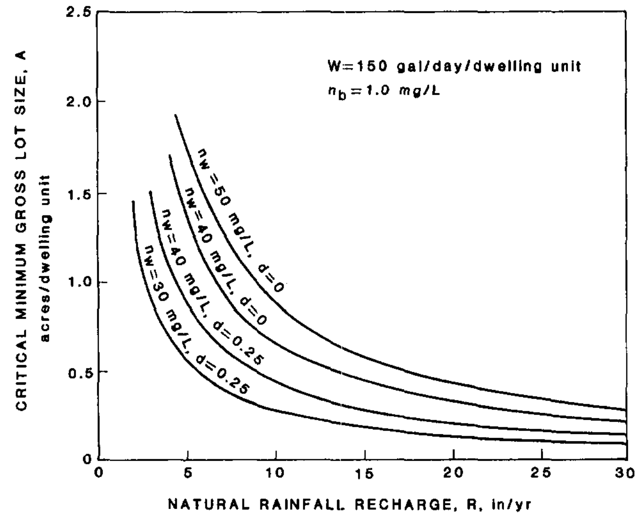

Fig. 2. Influence of effluent quality, denitrification, and rainfall recharge on critical lot size.

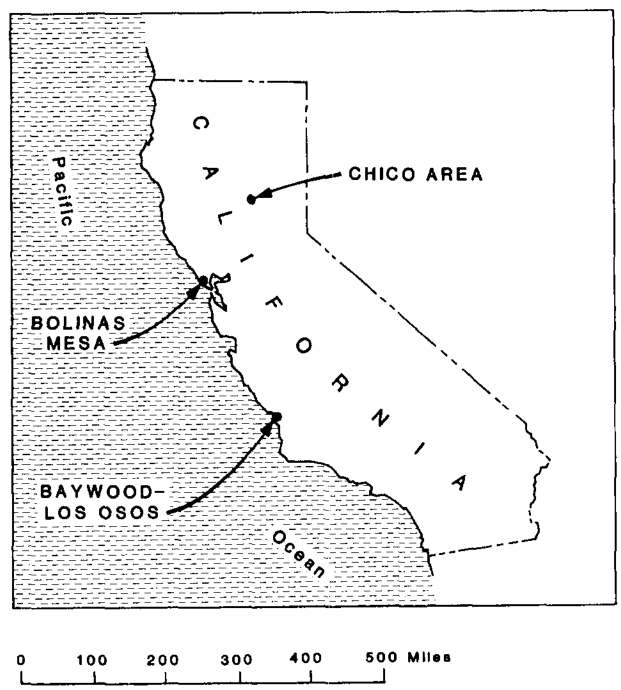

Fig. 3. Location of three case study communities in California.

Table 1. Physical Characteristics of the Case Study Areas

Characteristic	*Bolinas Mesa area*	*Chico area*	*Baywood/Los Osos*
Landform	Marine terrace	Valley floor	Coastal dune
Topography	0 to 5%	0 to 2%	3 to 5%
Soils	Sandy loam and sandy clay loam	Sandy loam	Loamy sands and sand
Depth to ground water (ft)	2 to 6	15 to 20	15 to 30
Average rainfall (in./yr)	30.9	22.5	20.0
Estimated rainfall recharge (in./yr)	14.4	16.8	12.0

Sources: see text.

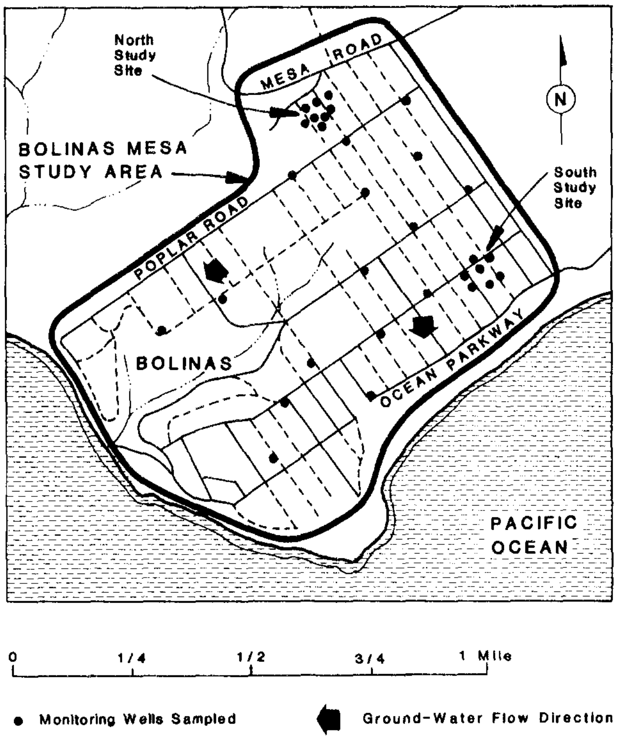

Fig. 4. Map of Bolinas Mesa study area.

Bolinas Mesa

The Bolinas Mesa area is a residential subdivision of approximately 240 acres located about 15 miles north of San Francisco. Initially created in the early 1900s, there are presently about 320 single family residences in the subdivision, on lots ranging from about 4,000 to 20,000 square feet in area (Figure 4). The subdivision occupies a coastal terrace, consisting of about 10 to 30 feet of sandy marine terrace deposits, overlying a gently sloping, relatively impermeable shale bedrock surface (Questa, 1987). Ground water collects in the terrace deposits as a result of local rainfall percolation, forming an unconfined water-table aquifer which varies from about five to 20 feet in saturated thickness. The water table fluctuates seasonally, rising typically to within two to four feet of ground surface during the winter months, and receding to depths of five to 10 feet or more during the summer and fall. The topography of the Bolinas Mesa is such that there are no streams or other significant sources of ground-water recharge that originate from outside of the immediate subdivision vicinity, making the study area relatively isolated from a hydrological perspective.

Chico Area

The Chico study area consists of approximately 4,550 acres (7.1 square miles) surrounding the City of Chico, located in the northern part of the Sacramento Valley (Figure 5). The city itself is served by a central sewage treatment facility, so it is not considered part of the study area. The area around the city consists of a mix of single and multifamily residential units and commercial development, with a density of approximately three dwelling units per acre (CSWRCB, 1989). The Chico area is situated on recent alluvial fan materials derived from volcanic sediments and mudflows originating in the hills to the east of Chico (DWR, 1984). The alluvial deposits average about 40 to 50 feet in thickness and consist of unconsolidated cobbles, gravel and sand, and minor amounts of clay. These deposits support a shallow unconfined aquifer that is recharged directly by infiltration from precipitation, local runoff, and discharge from subsurface sewage disposal. Older alluvium immediately underlies the recent alluvium and extends to depths of nearly 450 feet. It is characterized mostly by thick clay layers and cemented sand and gravel. In this zone, ground water occurs mainly in thin uncemented sand and gravel lenses under semiconfined conditions, recharged by vertical leakage from the overlying recent alluvium and from incised streams east of Chico.

Baywood-Los Osos

The Baywood-Los Osos area is an unincorporated coastal community located west of the City of San Luis Obispo, immediately south of Morro Bay (Figure 6). The majority of the area was subdivided largely for residential development in the early 1900s but significant development did not occur until the 1950s. The area impacted by on-site sewage disposal systems comprises about 2,350 acres, with a present density of approximately two to two and a half dwelling units per acre, and typical lot sizes in the range of 5,000 to 10,000 square feet (CRWQCB, 1983). The Baywood-Los Osos community is situated in the western end of Los Osos Valley, in an area dominated by marine sediments and dune deposits (DWR, 1973; Zipp, 1979). The valley is believed to consist of a single, unconfined aquifer system with a few isolated confined areas. The primary aquifer consists of alluvium, sand dune deposits, and a thick underlying siltstone known as the Paso Robles Formation. The sand dune deposits are as much as 250 feet in thickness and, historically, this formation has served as the principal source of supply to pumping wells. The water table in the area occurs at depths ranging typically from 15 to 30 feet below ground surface.

Summary

Table 2 summarizes, for each of the three study areas, the development characteristics that are pertinent to the assessment of nitrate loading impacts. For Chico and Baywood-Los Osos the data and calculated quantities are shown for the respective study areas as a whole. For the Bolinas Mesa area, data are also shown for two smaller subareas within the overall study area which are labeled, respectively, the North and South study sites. This was possible because of the very site-specific data available for these two subareas. No similar subarea data were readily available for the Chico and Baywood-Los Osos study areas.

The overall land area and the number of dwelling units for each area were obtained from maps and published documents prepared by the various county and state agencies that have studied the respective areas. The density (dwelling units per acre) and average gross acreage per lot (acres per dwelling unit) were computed directly from the given figures

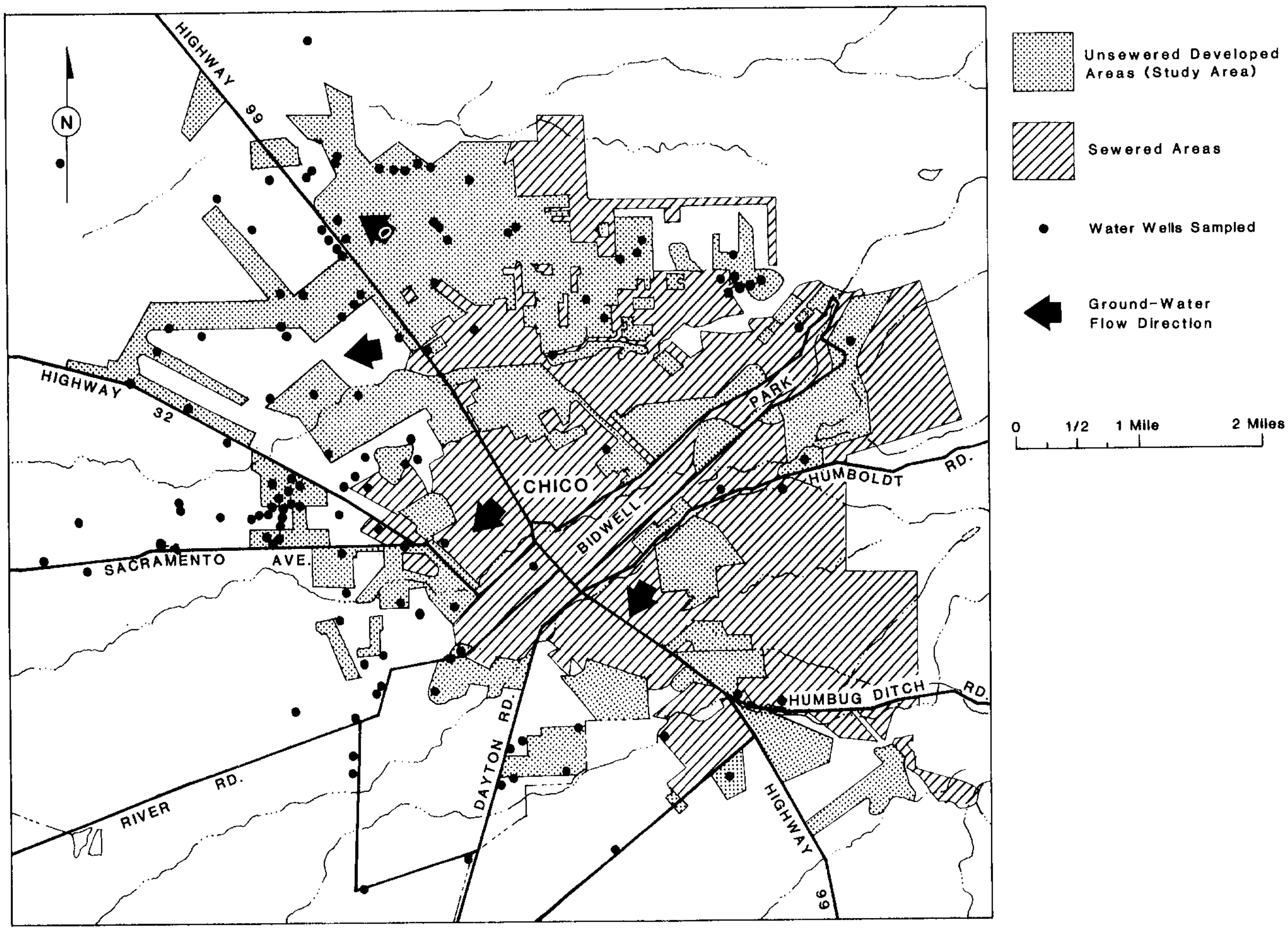

Fig. 5. Map of Chico study area.

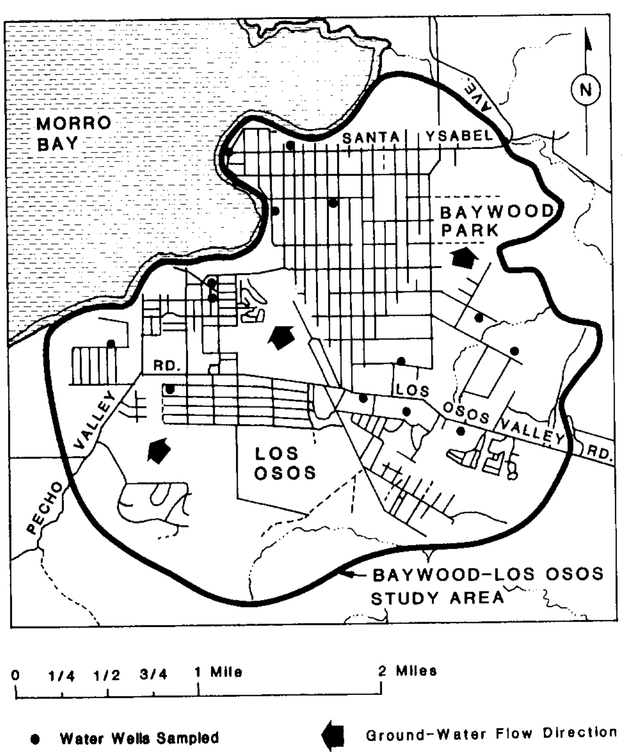

Fig. 6. Map of Baywood-Los Osos study area.

for land area and dwelling units. The waste-water loading (inches/year) reflects the discharge from all existing waste-water systems, averaged over the entire study area. An assumption of 150 gpd/DU was used for this calculation. The final entry expresses the waste-water loading, I, as a fraction of the annual rainfall recharge, R, for each study area (from Table 1).

Ground-Water Quality Data

In each of the three study areas, the effects of septic systems on ground-water quality have been a concern of the local health department and the respective California Regional Water Quality Control Board (there are nine such Regional Boards in California). As a result of these concerns, water quality sampling programs were conducted (DWR, 1984; CSWRCB, 1989; CRWQCB, 1983/84; Questa, 1987). Representative data compiled from these sampling programs are summarized in Table 3.

For the Bolinas Mesa area, some 30 ground-water monitoring wells were installed in the shallow marine terrace aquifer specifically for the purpose of monitoring septic system effects on ground waters. Well locations are shown on Figure 4. Samples were collected during the 1985-86 water year (October-September) and were analyzed for nitrate-nitrogen, ammonia, and total Kjeldahl nitrogen

Table 2. Development Characteristics of the Case Study Areas

Characteristic	Bolinas Mesa area: North study site	Bolinas Mesa area: South study site	Bolinas Mesa area: Area wide	Chico area	Baywood/Los Osos
Land area (acres)	2.75	1.72	240	4,550	2,350
No. of dwelling units (DU)	8	9	320	13,650	5,170
Density (DU/gross acre)	2.9	5.2	1.3	3.0	2.2
Gross average acreage per lot, A (acres)	0.34	0.19	0.69	0.33	0.45
Average waste-water loading over gross area, I (in./yr)	5.8	10.5	2.6	6.0	4.4
Relative waste-water loading, I/R	0.40	0.73	0.18	0.35	0.37

Sources: see text.

Table 3. Ground-Water Nitrate-Nitrogen Data Summary

Study area	Density of wells sampled (wells per acre)	No. of wells sampled	Total samples	Range of NO_3-N concentrations (mg/l): Minimum	Mean	Maximum
Bolinas Mesa						
• North study site	2.55	7	21	1.5	11.7	64.9
• South study site	4.07	7	21	1.5	13.9	51.0
• Total area	0.125	30	58	0.7	5.3	64.9
Chico area	0.0286	130	289	0.0	9.6	40.6
Baywood-Los Osos						
• Upgradient wells	0.00511*	6	21	0.0	4.5	13.4
• Downgradient wells	0.00681*	8	32	0.0	10.4	40.0

*Based on estimated apportionment of total area.
Sources: See text.

(Questa, 1987). The monitoring wells representing conditions in the North and South study sites were sampled three times, and the others were sampled once. Table 3 shows the total nitrogen expressed as NO_3-N, assuming that the other forms of nitrogen, which occur in small quantities, will in time convert to nitrate within the ground water. These values were obtained by summing the nitrate-nitrogen and total Kjeldahl nitrogen data.

Nitrate-nitrogen data for the Chico area were obtained from the sampling of existing water-supply wells located within the defined study area, and drawing from the shallow ground-water zones. Well locations are shown on Figure 5. These data were obtained and reported by the California Department of Water Resources, Department of Health Services and Regional Water Quality Control Board during the period of 1984-1989 (DWR, 1984; CSWRCB, 1989).

The data shown for Baywood-Los Osos were obtained from a special monitoring study conducted by the California Regional Water Quality Control Board during 1983-1984 water year (CRWQCB, 1983/84). Samples were obtained quarterly from a network of wells completed in the upper aquifer; these included active water-supply wells and monitoring wells. The wells were distributed relatively uniformly over the Baywood-Los Osos area, as shown on Figure 6. In comparison with the other two study areas, in the Baywood-Los Osos area a significantly larger fraction of the monitoring wells (6 out of 14) is upgradient of the major concentration of development; these wells are shown in the southeast quadrant of Figure 6. Therefore, the data are shown separately for the upgradient and downgradient group of wells. The downgradient wells would be expected to show the full effect of nitrate-nitrogen additions from the entire developed area.

Comparison with Predicted Values

The mean values for nitrate-nitrogen shown in Table 3 represent, for each of the study areas and subareas, the resultant concentration that may be compared with predicted values obtained from equation (1). A graphical plot of the mean nitrate-nitrogen data for the various areas is provided in Figure 7; for comparison with predicted values, the curves of Figure 1 are included.

As indicated, the observed values for all areas, except the upgradient wells for Baywood-Los Osos, fall within the envelope defined by the curves of predicted values. This evidence of close correspondence between actual and predicted values confirms the validity of this method for estimating the area-wide nitrate effects on ground water from on-site sewage disposal systems.

With respect to the upgradient group of wells for Baywood-Los Osos, one would expect the nitrate-nitrogen concentration to be considerably less than that predicted by equation (1), because these wells are not affected by the majority of the development in the study area. This is borne out by the results in Table 3 and Figure 7, which show that the mean nitrate-nitrogen concentration in the upgradient wells is 43 percent of that observed in the downgradient wells.

Discussion

Factors to be considered when using the simplified mass balance method presented in this paper include the following:

1. The method incorporates only the vertical component of ground-water recharge, ignoring any dilution effects of lateral ground-water inflow from upgradient areas. From a planning and regulatory perspective, this is an appropriate, conservative (worst case) approach. One must consider that the nitrate-nitrogen concentrations in ground-water inflow from upgradient areas may also increase over time in response to waste-water loading or other land use activities in those areas, thus making unreliable any estimates of the degree of dilution due to lateral ground-water inflow. In circumstances where lateral ground-water inflow is determined to be significant and can be assigned a reliable constant long-term nitrate-nitrogen concentration, then the use of a mass balance model which includes such a lateral flow component, e.g., Wehrmann (1984), may be appropriate. However, even in such cases, the vertical recharge from waste water and rainfall will tend to accumulate and remain in a layer at the water table, largely unaffected by lateral inflow. This is due to the slow vertical mixing that occurs in horizontal ground-water flow. Use of the methods in this paper will protect against nitrate-nitrogen concentrations in such upper layers exceeding safe limits.

2. The nitrate-nitrogen concentrations predicted by the methods of this paper are long-term values. First, the development of an area to its ultimate density and waste-water loading rates may take many years. Second, depending upon the thickness and nature of the unsaturated zone, the travel time of effluent to the water table could vary from days to years. Finally, where the vertical recharge of waste water and rainfall adds to ground water in deep aquifers having little lateral flow, deep mixing will be a long-term process. Such deep mixing could be caused by deep pumping wells, leakage to even deeper aquifers, and ground-water outflow.

3. The predictive equations are intended to be used to evaluate average, area-wide ground-water conditions. They do not yield results that can be applied to a single point, such as might be required for siting or protecting an individual well. This would entail a more detailed analysis of the areal and vertical distribution of nitrate-nitrogen in the ground water.

4. The simplified methods here do not explicitly account for other identifiable sources of nitrate-nitrogen, such as animal wastes and fertilizer applications. Livestock wastes contain very high levels of nitrogen which may be a significant contributor to ground-water nitrate-nitrogen concentrations, depending upon livestock densities, soil conditions, and waste handling practices. Wastes produced by a single horse, for example, contain twice as much nitrogen as that from a typical household. This potential source should be added to the mass balance analysis when considering areas where significant livestock populations exist or can be expected within the development area.

Lawn fertilizers contribute much less nitrate-nitrogen than do livestock. For typical residential subdivisions and rural communities, a reasonable assumption is that about 10 percent of the gross area is landscaped with turf that is fertilized. The nitrogen fertilizer rate for well-kept lawns is estimated by nurseries to be about 40 to 65 lbs per year per acre of turf. Typically, 50 to 75 percent of the applied nitrogen can be expected to be consumed by plant uptake and soil denitrification (WPCF, 1990). The resultant loading to ground water is then approximately in the range of 1 to 3 lbs per year per developed acre. For an assumed rainfall recharge rate of 12 inches/year, the resultant nitrate-nigrogen concentration from the leaching of fertilizer would be about 0.37 to 1.1 mg/l. In the simplified methods of this paper, this is considered to be substantially accounted for in the assumption of a background nitrate-nitrogen concentration of 0.5 to 1.0 mg/l. Where substantial portions of the site are devoted to turf, special accounting may need to be made for fertilizer nitrate-nitrogen contributions. Mass balance models by Tinker (1991) and the Center for Environmental Research (1985) incorporate a turf fertilizer component.

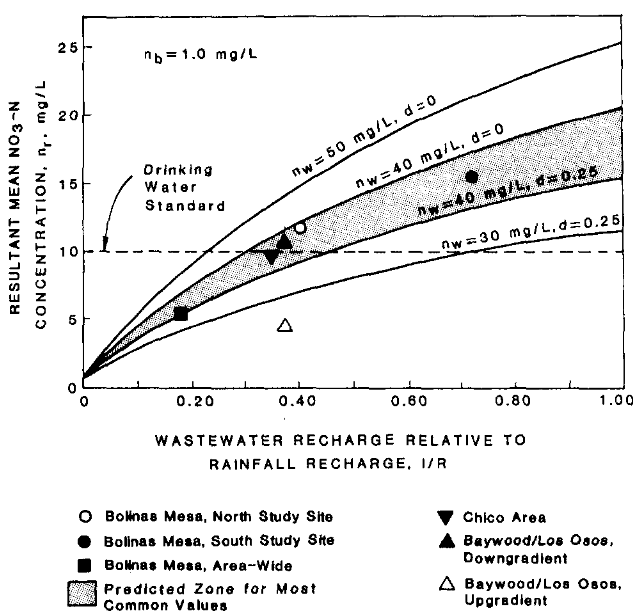

Fig. 7. Comparison of actual and predicted nitrate-nitrogen concentrations in ground water.

5. The curves of Figures 1 and 2 show the strong influence of the rainfall recharge component on the resultant nitrate-nitrogen concentration. The application of the methods presented in this paper and the reasonableness of the results are, therefore, limited by the accuracy with which the rainfall recharge fraction can be estimated or determined by the user. For best results, the user should perform a thorough water balance analysis using techniques such as those developed by the U.S.D.A. Soil Conservation Service (1964) or Thornthwaite and Mather (1955), or other information based on local studies.

Planning Applications

The nitrate assessment procedures outlined in this paper may have a number of land use and environmental planning applications. A principal advantage is the minimal requirement for data.

Zoning and Subdivision Proposals

Preliminary evaluation of potential water quality impacts is useful when broad land use planning decisions are being made. Computation of A or use of Figure 2 can provide an initial basis for determining appropriate development densities to assure protection of areal ground-water quality.

Residential subdivision proposals can be screened for potential long-term nitrate impacts by applying equations (1) and (2). The North Coast Regional Water Quality Control Board of California and several local health departments have adopted these procedures for this purpose. An indication of no potentially excessive nitrate buildup in ground water according to the analyses presented in this paper would obviate the need for further study. In the event that preliminary analyses indicate possible problems (e.g., planned development density exceeds $1/A$), further analyses might be required to define the ground-water system and potential effects more specifically. Also, mitigation measures and ground-water monitoring requirements may be formulated based on the preliminary nitrate predictions. Possible mitigation measures might include reducing development and sewage loading densities, incorporating nitrogen removal systems (Laak, 1982), or modifying the disposal system locations or design (Harkin et al., 1979).

Buildout in Existing Unsewered Areas

Continued buildout of certain existing development areas using on-site sewage disposal systems may pose significant long-term ground-water nitrate concerns. In cases where development density is approaching critical levels predicted by equation (2), then further analysis of possible localized problems and more complete study of the ground-water system is warranted. Ground-water monitoring may be used to verify the water quality concerns indicated by the predictive equations. The preliminary analyses using equations (1) and (2) provide a rational basis for the design of field monitoring programs. Specific mitigation measures, including modified design standards, might be appropriate for any additional development that would tend to aggravate observed ground-water quality problems.

Conclusions

The accumulation of nitrate in the upper saturated zone is a cumulative effect of on-site sewage disposal practices which has not been addressed by standard siting and design criteria. This paper presents a convenient method for estimating long-term increases in ground-water nitrate-nitrogen caused by on-site sewage disposal. The method is useful to practicing engineers and regulatory agencies for the general planning and evaluation of residential developments as well as for the site-specific design of on-site sewage disposal systems. This is evidenced by their adoption in parts of California.

The greatest potential for ground-water nitrate-nitrogen problems arises in areas of low rainfall recharge and high development density. The situation may be critical if local ground waters are used for domestic water supply. Existing communities and cluster developments using large, common septic tank disposal fields are also likely to be of significant concern because of the high concentration of waste-water disposal in a limited area. In newer developments, mandatory space requirements for roads, buildings, open space, etc., will sometimes keep the overall intensity of development and waste-water application below critical levels.

Comparison of predicted values with actual field sampling data for several case study locations in California confirms that the methods provide reasonable first approximations of nitrate-nitrogen effects in ground water from septic tank disposal fields. The agreement between predicted and observed values is sufficient to enable potential areas of concern to be identified, thus making the method an effective planning tool.

A promising application of these nitrate assessment procedures is for regulatory purposes. The limited data requirements and straightforward computations make the approach widely suitable for evaluation of zoning and land use plans, subdivision proposals, and continued development in unsewered areas. The need for mitigation measures, long-term monitoring, or more detailed site investigations can also be readily determined by use of these procedures.

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Storage and mobilization of natural and septic nitrate in thick unsaturated zones, California

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SUMMARY

Mobilization of natural and septic nitrate from the unsaturated zone as a result of managed aquifer recharge has degraded water quality from public-supply wells near Yucca Valley in the western Mojave Desert, California. The effect of nitrate storage and potential for denitrification in the unsaturated zone to mitigate increasing nitrate concentrations were investigated. Storage of water extractable nitrate in unsaturated alluvium up to 160 meters (m) thick, ranged from 420 to 6600 kilograms per hectare (kg/ha) as nitrogen (N) beneath undeveloped sites, from 6100 to 9200 kg/ha as N beneath unsewered sites. Nitrate reducing and denitrifying bacteria were less abundant under undeveloped sites and more abundant under unsewered sites; however, $\delta^{15}N$–NO_3, and $\delta^{18}O$–NO_3 data show only about 5–10% denitrification of septic nitrate in most samples—although as much as 40% denitrification occurred in some parts the unsaturated zone and near the top of the water table. Storage of nitrate in thick unsaturated zones and dilution with low-nitrate groundwater are the primary attenuation mechanisms for nitrate from septic discharges in the study area. Numerical simulations of unsaturated flow, using the computer program TOUGH2, showed septic effluent movement through the unsaturated zone increased as the number and density of the septic tanks increased, and decreased with increased layering, and increased slope of layers, within the unsaturated zone. Managing housing density can delay arrival of septic discharges at the water table, especially in layered unsaturated alluvium, allowing time for development of strategies to address future water-quality issues.

1. Introduction

Nitrate contamination of groundwater is an important issue in many parts of the United States (Madison and Brunett, 1985; Power and Schepers, 1989; Mueller and Helsel, 1996; Nolan et al., 2002; McMahon and Böhlke, 2006; Harter and Lund, 2012) and elsewhere in the world (World Health Organization, 1985; Spaulding and Exner, 1993; Almasri, 2006; Joekar-Niasar and Ataie-Ashtiana, 2008; Yonghai and others, 2009). High nitrate concentrations in drinking water can cause methemoglobinemia in human infants, and nitrate concentrations only slightly above natural background have been associated with increased risk of spontaneous abortion, bladder and ovarian cancer, and non-Hodgkin's Lymphoma (Nolan et al., 2002). Health concerns associated with nitrate in drinking water have prompted the establishment of a Maximum Contaminant Level (MCL) for nitrate of 10 milligrams per liter as nitrogen (mg/L as N) by the U.S. Environmental Protection Agency (2009) and similar guidelines for drinking water by the World Health Organization (2007).

Although widespread exposure to nitrate concentrations above the MCL in drinking water is relatively rare in the United States, a nationwide survey of untreated water from domestic and public supply wells showed nitrate was the most frequently detected regulated contaminant (Squillace et al., 2002; U.S. Environmental Protection Agency, 2005). Nitrate derived naturally from precipitation, soils, and geologic sources generally occurs in groundwater at concentrations from less than 1 to 3 mg/L as N (Mueller and Helsel, 1996; Dwivedi et al., 2007; Dubrovsky et al., 2010). Concentrations in excess of natural values commonly result from agricultural use of chemical or organic fertilizer, improper containment and disposal of manure, or discharge of treated sewage from septic systems.

About one-fourth of homes in the United States are served by septic systems and discharges from septic systems have been estimated to exceed 4 billion gallons per day (U.S. Environmental Protection Agency, 2002). Even when properly functioning, septic discharges are a source of nitrate to underlying aquifers.

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McQuillan (2004) showed that in New Mexico more wells are contaminated by nitrate associated with on-site disposal of septic waste than all other contaminants combined. In areas receiving septic discharges the load of nitrate to underlying aquifers is a function of septic tank density (Bicki and Brown, 1991; Yates, 1985; Viers et al., 2012). A number of studies have been done in a range of hydrologic settings to determine optimal septic tank densities and minimum lot sizes necessary to protect groundwater from nitrate contamination in unsewered areas (Woodward et al., 1961; Perkins, 1984; Umari et al., 1993). Results of these studies are scale dependent and commonly incorporate the effect of dilution from infiltration of precipitation, dilution with shallow groundwater, and nitrogen losses from denitrification on the nitrate concentration in shallow groundwater resulting from septic discharges.

Groundwater recharge from precipitation is small or non-existent in arid areas, and septic discharges are an important source of recharge to underlying aquifers. In these areas, dilution from infiltration of precipitation is scant—leaving only dilution with shallow groundwater or denitrification to mitigate nitrate associated with septic discharges. In arid areas, nitrate contamination from septic discharges may be damped by long travel times through thick unsaturated zones, and subsequent storage of high-nitrate water in the unsaturated zone. Previous work in Yucca Valley, Calif. showed nitrate from septic discharges stored in the unsaturated zone could be rapidly mobilized as a result of artificial recharge and subsequent rising groundwater (Nishikawa et al., 2003). Although denitrification is limited to anoxic environments, denitrification in perched layers and anoxic microsites within unsaturated zones may occur as septic discharges infiltrate to the water table (Umari et al., 1993). To the extent denitrification occurs, it may act to remove nitrate from the unsaturated zone and limit the sudden release of nitrate to groundwater if the water table rises rapidly as a result of natural or artificial recharge. The source of ammonia and nitrate, and the extent of nitrification and denitrification can be identified on the basis of the stable isotope ratios of nitrogen in ammonia ($\delta^{15}N–NH_4$) and nitrate ($\delta^{15}N–NO_3$) and the stable isotope ratio of oxygen in nitrate ($\delta^{18}O–NO_3$) (Aravena and Robertson, 1998; Choi et al., 2003). The chemical and microbiological processes that control the form of nitrogen and isotopic composition are described in the supplementary on-line material.

The purpose of this study was to assess nitrate storage, potential for denitrification, and management of nitrate within thick unsaturated zones underlying undeveloped, and unsewered land uses in an area of rising water levels resulting from managed aquifer recharge. Sites irrigated with dairy wastewater sites were included in the study as an end-member receiving high waste loads where nitrate reduction and denitrification were likely to occur.

Field work included: test drilling, instrument installation, and collection of geologic, geophysical, water potential, and water-quality data from the unsaturated zone and near the water-table interface at sites beneath a range of land uses in the western Mojave Desert. Analytical work included (1) analyses of water extracts from unsaturated alluvium, (2) analyses of unsaturated zone water, groundwater, and unsaturated zone gasses, (3) enumeration of nitrate-reducing and denitrifying bacteria, and (4) analysis of nitrogen and oxygen isotopes in the nitrate molecule. The study also included numerical modeling of unsaturated zone flow and nitrate transport beneath septic tanks to investigate management alternatives to help mitigate increasing nitrate concentrations.

2. Hydrogeology

The study area is in the western Mojave Desert of California near the communities of Yucca Valley and Joshua Tree, about 180 km (km) east of Los Angeles, Calif., and near El Mirage, about 80 km northeast of Los Angeles (Fig. 1). The communities are within the Warren, Joshua Tree, and El Mirage Valley Groundwater Subbasins, respectively (California Department of Water Resources, 2004). In 2005, population in Yucca Valley, and Joshua Tree, was

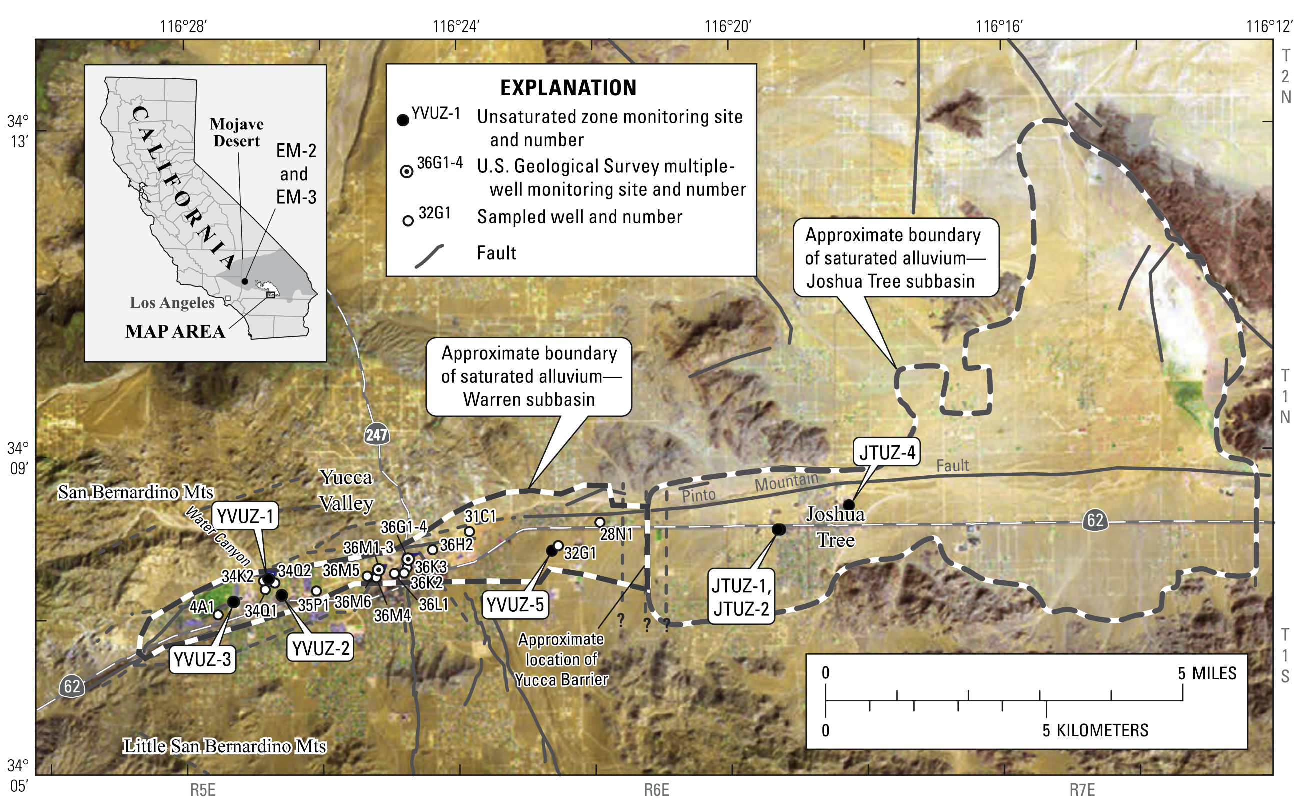

Fig. 1. Study area location.

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about 19,700, and 9000, respectively. Population in these communities is expected to increase almost 40% by 2020 (LSA Associates, 2008). Land use in Yucca Valley and Joshua Tree is primarily residential and commercial. There was no agricultural land use and, with the exception of a small golf course in the Yucca Valley area, no irrigated land use. Almost all the nitrate in groundwater was derived from either natural sources or septic discharges. Population in the El Mirage area is less than 5000. Rural residential and agricultural land use, including dairies, predominates in the El Mirage area.

The western Mojave Desert is characterized by cool, wet winters and hot, dry summers. Winter low temperatures are commonly below 0 °C, and summer high temperatures can exceed 45 °C. Average annual precipitation (1971–2000) ranges from about 150 mm (mm) in El Mirage and Yucca Valley, to 110 mm in Joshua Tree (Western Region Climate Center, 2009). Most precipitation falls in the winter months although summer monsoonal precipitation occurs, especially near Joshua Tree. Precipitation is insufficient to result in areal recharge to the alluvial aquifers, although infiltration of focused runoff in intermittent streams can result in small amounts of recharge (Izbicki, 2007; Izbicki et al., 2007; Nishikawa et al., 2004). As a result of dry conditions soluble salts, such as chloride and nitrate, have accumulated in the unsaturated zones (Izbicki et al., 2000a,b, 2002, 2007).

Alluvial deposits in the Yucca Valley and Joshua Tree area consist of poorly sorted sand and gravel with interbedded layers of silt and clay (Nishikawa et al., 2003, 2004). Alluvial deposits near the margins of the alluvial basins are more poorly-sorted than deposits in the center of the valley. Depth to water is commonly about 120 m below land surface in the Yucca Valley and Joshua Tree areas. Alluvial deposits in the El Mirage area are finer-grained and consist primarily of silt with interbedded layers of sand and gravel. Depth to water is about 10–30 m in the El Mirage area.

Groundwater is pumped for public supply in Yucca Valley and Joshua Tree, and for domestic and agricultural supply in El Mirage. Groundwater pumping has caused water-level declines as great as 100 m in parts of Yucca Valley (Stamos et al., 2013), 11 m in parts of Joshua Tree (Nishikawa et al., 2004), and 6 m in parts of El Mirage (Teague et al., 2013). Water-level declines in Yucca Valley have caused wells to go dry, prompting the importation of water. Infiltration of imported water from ponds to recharge the basin caused the water table to rise and to intercept high-nitrate water from septic sources in the unsaturated zone. This increased nitrate concentrations in some wells to greater than the MCL of 10 mg/L as N (Nishikawa et al., 2003). Water level declines in the Joshua Tree area are not so severe that wells have gone out of production, but importation of water is planned to mitigate declining water levels that area.

During the study, three ponds having a combined area of 2.8 hectares (ha) were constructed at YVUZ-1 by the local water district. Between June 7, 2006 and October 29, 2007 6.4×10^6 cubic meters (m^3) of imported water was infiltrated from the ponds (Stamos et al., 2013). A smaller pond having an area of 0.06 ha was constructed adjacent to YVUZ-5, and between November 12, 2008 and June 16, 2009 38,600 m^3 of local groundwater was infiltrated from the pond to evaluate the suitability of the site for infiltration of treated wastewater.

3. Methods

3.1. Study sites and field methods

Nine unsaturated zone boreholes (Fig. 2) were drilled as part of this study using the ODEX (Overburden Drilling EXploration) method (Driscoll, 1986; Hammermeister et al., 1986; Izbicki et al., 2000a) with a U.S. Geological Survey drill rig and crew. Sites included undeveloped land use (EM-3, JTUZ-4, YVUZ-1, YVUZ-5), unsewered residential and commercial land use (JTUZ-1, JTUZ-2, and YVUZ-2), a former golf course (YVUZ-3), and a site irrigated with dairy wastewater (EM-2). The dairy wastewater site was included in the study as an end-member receiving high waste loads where nitrate reduction and denitrification were likely to occur. Boreholes at most sites were drilled into the water table, and drill depths ranged from 12.5 to 163 m (Table 1).

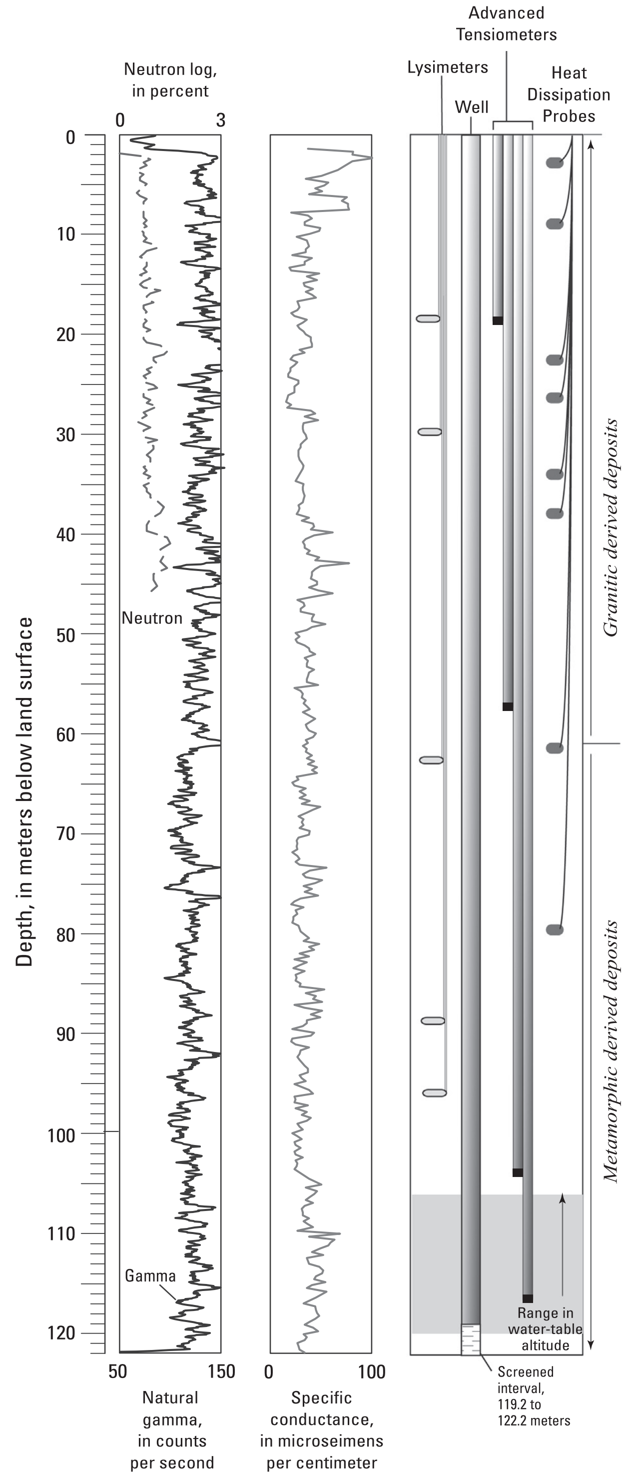

Fig. 2. Selected geologic and geophysical logs, and instrument placement in unsaturated-zone monitoring site YVUZ-1, Warren Groundwater Subbasin, western Mojave Desert, California.

Table 1
Unsaturated zone study sites, Warren, Joshua Tree, and El Mirage Valley Groundwater Subbasins, western Mojave Desert, California, 2004–2014.

Site name	Latitude (dd′mm″ss°)	Longitude (dd′mm″ss°)	Ground-water subbasin	Date drilled (mm/yy)	Land use, at time of drilling	Drill depth, in meters	Range in depth to water, in meters	Nitrate as nitrogen storage in unsaturated zone, in kilograms per hectare	Comments
YVUZ-1	34′07″34°	116′26″43°	Warren Valley	9/04	Undeveloped	121.9	90.4–120.6	570	Imported water infiltrated from recharge pond at site beginning June 7, 2006
YVUZ-2	34′07″18°	116′26″37°	Warren Valley	9/04	Unsewered mixed high-density residential and commercial	115.5	75.8–102.8	6150	Water levels increasing as a result nearby recharge throughout the study
YVUZ-3	34′07″15°	116′27″19°	Warren Valley	10/04	Golf course	12.5		–	Irrigation on golf course stopped in 2007
YVUZ-5	34′07″51°	116′22″28°	Warren Valley	7/08	Undeveloped	118.9	111.9–112.8	420	Local water infiltrated from adjacent test pond beginning November 12, 2008
JTUZ-1	34′07″56°	116′19″06°	Joshua Tree	7/07	Unsewered residential	162.6	157.8–158.1	9210	Influenced by upslope residential septic discharges
JTUZ-2	34′07″56°	116′19″17°	Joshua Tree	7/07	Unsewered residential	24.6			Adjacent to residential septic system
JTUZ-4	34′08″24°	116′18″07°	Joshua Tree	4/08	Undeveloped	133.5	127.3–128.2 (01/11–5/14)	6610	Imported water proposed to be infiltrated from recharge ponds at site
EM-2	34′36″19°	117′35″59°	El Mirage Valley	9/06	Irrigated with dairy wastewater	21.3	15.9–16.3	11600	Historically irrigated with dairy wastewater
EM-3	34′36″46°	117′35″45°	El Mirage Valley	9/06	Undeveloped	17.0	10.7–11.5	1070	Irrigation with dairy wastewater beginning in Spring 2008

Groundwater subbasin designation from California Department of Water Resources, Bulletin 118, http://www.water.ca.gov/groundwater/bulletin118/gwbasin_maps_descriptions.cfm, accessed July 15, 2014.

Drilling was coordinated with sample collection to allow collection of cuttings at 0.3 m intervals. Cuttings and core material collected during drilling were described in the field and preserved for laboratory analysis for physical properties, water extractable anions, and microbiology including denitrifying and nitrate-reducing bacteria abundances. Detailed description of drilling, collection and analyses of cutting and core material, and instrument installation is provided in the on-line supplementary material.

Water samples were collected from production wells, monitoring wells, and suction-cup lysimeters. Field parameters were measured and samples were filtered and preserved in the field for laboratory analyses for chemical and isotopic composition. Samples were analyzed for major ions, selected minor ions, selected trace elements, and nutrients (including the different chemical forms of nitrogen and phosphorous using methods described by Fishman and Friedman (1989), Fishman (1993), and Garbarino and others (2002, 2006). Samples also were analyzed for the stable isotopes of oxygen and hydrogen in water, nitrogen isotopic ratios in ammonia ($\delta^{15}N{-}NH_4$) (Hannon and Böhlke, 2008) and nitrate ($\delta^{15}N{-}NO_3$) (Revesz and Casciotti, 2007), and oxygen isotopic ratios in nitrate ($\delta^{18}N{-}NO_3$) (Revesz and Casciotti, 2007). Unsaturated zone gas samples were collected from instruments at selected sites and analyzed for selected atmospheric gasses including nitrogen, oxygen, and nitrous oxide.

Detailed descriptions of sample collection, and laboratory analytical procedures are provided in on-line supplementary material.

4. Results and discussion

4.1. Test-drilling, physical and hydraulic property data

Test-drilling data show the study sites are underlain by alluvial sand, gravel, silt, and clay in varying percentages. The coarsest-grained deposits composed largely of sand and gravel were at YVUZ-1, which was later developed for aquifer recharge. Unsaturated deposits at other sites in Yucca Valley and Joshua Tree were composed largely of sand and gravel, with interbedded layers of fine-grained material. Layering was greater on the sloping alluvial fan deposits along the south side of the Warren and the Joshua Tree Subbasins (YVUZ-5, JTUZ-1, and JTUZ-2). Deposits were better sorted and layering was less at the YVUZ-2 and JTUZ-4 sites near the center of the valley. The finest-grained deposits were at sites, EM-2 and EM-3, at the distal end of a large alluvial fan, which were composed largely of silt with interbedded layers of sand and gravel.

In general, the unsaturated zones beneath undeveloped sites were dry with highly negative matric potentials. The exception was the YVUZ-1 site near the mouth of Water Canyon. Infiltration of intermittent streamflow at this site increased water content within the unsaturated zone, matric potentials were less negative, and gravity drainage toward the water table occurred throughout the unsaturated zone. Water contents also were greater and matric potential less negative within the unsaturated zones beneath unsewered residential and commercial sites (JTUZ-1, JTUZ-2, and YVUZ-2). However, moist layers at these sites were often interspersed with drier intervals having more negative matric potentials. The exception was JTUZ-2, adjacent to a residential septic system; although the site was not drilled to the water table (almost 158 m below land surface), the unsaturated zone was comparatively moist throughout the 24.6 m drill depth. Similarly, the unsaturated zone underlying EM-2, irrigated with dairy wastewater, was moist throughout, with occasional perched layers on fine-grained deposits within the unsaturated zone. At most sites, the water table declined in recent years prior to the study as a result of groundwater pumping; as a consequence, water contents were often higher and matric potentials less negative between the predevelopment water table and the present-day water table than in overlying deposits.

Detailed descriptions of lithology, hydraulic property, water potential and other data for the YVUZ-1, YVUZ-2, and YVUZ-3 sites are available in Stamos et al. (2013), for the JTUZ-1 and JTUZ-2 sites in Burgess et al. (2012), and the EM-2 and EM-3 sites by Izbicki (2008). Data for the YVUZ-5 site are unpublished but available in the USGS San Diego office files. Hydraulic property data from sites JTUZ-1, JTUZ-2, and YVUZ-5 were used for model development discussed later in this manuscript. Additional geologic and geophysical data collected at the time of drilling are available on file at the U.S. Geological Survey office in San Diego.

4.2. Water-extraction data and storage of nitrate in the unsaturated zone

Water extracts from alluvium underlying undeveloped sites, unsewered residential and mixed (high-density residential and commercial) development, a golf course and a site irrigated with dairy wastewater (Table 1) were used to assess storage of nitrate in the unsaturated zone.

4.2.1. Undeveloped sites

The YVUZ-1, YVUZ-5, JTUZ-4, and EM-3 sites were in areas of undeveloped land use at the time of installation (Table 1). Storage of nitrate in the unsaturated zone at YVUZ-5, JTUZ-4, and EM-3 sites was 420, 6610, and 1070 kilograms per hectare as nitrogen (kg/ha as N), respectively (Table 1). Typical of arid areas, where areal recharge from precipitation and gravity drainage to depths below the root zone does not occur, and consistent with accumulation of chloride near the base of the root zone, most nitrate was in the upper 5 m of the unsaturated zone. Nitrate concentrations at the YVUZ-5 site were as high as 2.5 milligrams per kilogram (mg/kg) (Fig. 3). In contrast, nitrate concentrations at the JTUZ-4 site were as high as 41 mg/kg (not shown in Fig. 3)—possibly as a result of the flat topography at the site near Yucca Wash, coupled with biological activity and recycling and accumulation of nutrients at land surface by bacterial communities—although surface features such as "desert pavement" associated with these communities (Graham et al., 2008) were not present. At each site there was an increase in nitrate concentrations associated with increased chloride concentrations about 15 m below land surface (Fig. 3) related to long-term deposition of nitrate, chloride, and other soluble salts in precipitation. Nitrate concentrations in the unsaturated zone below 20 m were generally lower than concentrations at shallower depths.

Land use at YVUZ-1 also was undeveloped; however, in contrast to YVUZ-5, JTUZ-4, or EM-3, intermittent infiltration from streamflow from Water Canyon occurs at YVUZ-1 and gravity drainage occurs throughout the entire unsaturated zone. Previous work has shown groundwater in this area contains tritium (a radioactive isotope of hydrogen with a half-life of about 12.3 years), suggesting that groundwater recharge occurs in this area under present-day climatic conditions (Izbicki and Michel, 2003). Chloride has not accumulated near the base of the root zone at YVUZ-1. Nitrate storage at this site is about 570 kg/ha as N and nitrate was distributed throughout the unsaturated zone to about 80 m below land surface. The largest concentration of nitrate occurs near this depth and was associated with increased natural gamma activity in logs collected during drilling consistent with geologic changes at depth (Fig. 2).

4.2.2. Unsewered residential sites

Land use at JTUZ-1 was unsewered residential. Land use at YVUZ-2 included nearby high-density residential and commercial land uses. The sites were drilled to slightly below the water table at depths of 158.8 and 102.8 m, respectively (Table 1). Nitrate concentrations in water extracts from alluvium in the unsaturated zone underlying the JTUZ-1 and YVUZ-2 sites were as high as 60 and 37 mg/kg as N of alluvium, respectively (Fig. 3). The highest concentrations at both sites were between 20 and 40 m below land surface and were associated with increased concentrations of chloride and other soluble salts. Total nitrate in storage at the JTUZ-1 and YVUZ-2 sites was 6150 and 9210 kg/ha as N, respectively.

Unsewered residential development near JTUZ-1 has discharged septic effluent since the mid 1950s. Nitrate concentrations at the water table are about 13 mg/L as N, and exceed the MCL for nitrate of 10 mg/L as N. Development near the YVUZ-2 site has discharged septic effluent since 1953. Matric potential data show gravity drainage from septic discharge extends at least to a depth of about 50 m. The unsaturated zone below this depth was drier. Nitrate concentrations at the water table near YVUZ-2 were near background concentrations of about 2 mg/L as N.

An additional site, JTUZ-2, was drilled adjacent to an active septic system near JTUZ-1 to a depth of 24.6 m (Table 1). Nitrate concentrations in water extracts from alluvium at JTUZ-2 averaged 0.8 mg/kg of alluvium. Matic potential data suggest that septic discharges maintain gravity drainage throughout the depth sampled by JTUZ-2. Data from YVUZ-2, JTUZ-1 and JTUZ-2 reflect nitrate storage beneath unsewered residential development with gravity drainage to deeper depths in areas adjacent to active septic discharges.

4.2.3. Other sites

The YVUZ-3 site underlies a golf course. The site was drilled to 12.5 m below land surface, the depth to water at the site is about 120 m below land surface. Nitrate concentrations in the upper 12.5 m of the unsaturated zone were as high as 5.9 mg/kg of alluvium, and the mass of nitrate in the upper 12.5 m of the unsaturated zone at YVUZ-3 was 630 kg/ha as N. Although it was not possible the calculate the total mass of nitrate in the unsaturated zone at this location, the mass in the upper 12.5 m is not as high as comparable intervals at undeveloped sites JTUZ-4 or EM-3—suggesting that naturally-occurring nitrate and nitrate applied with fertilizer at this site may have infiltrated to greater depths within the unsaturated zone.

The EM-2 site underlies an alfalfa field historically irrigated with dairy wastewater. The site was drilled to 21 m, slightly below the water table at about 16 m below land surface. Nitrate concentrations in the unsaturated zone at EM-2 were as high as 61 mg/kg of alluvium, and the mass of nitrate in the unsaturated zone at EM-2 was 11,600 kg/ha as N (Table 1). Despite the relatively thin unsaturated zone at this site the nitrate load was the highest measured as part of this study. Nitrate concentrations as high as 62 mg/L as N in the underlying water table aquifer suggest that dairy wastewater has reached the water table at this site.

4.3. Nitrate reducing and denitrifying bacteria

Nitrate reducing and denitrifying bacteria were measured in unsaturated alluvium from two undeveloped sites (YVUZ-1, YVUZ-5), from three unsewered sites (JTUZ-1, JTUZ-2, and YVUZ-2), and from a field irrigated with dairy wastewater (EM-2). Nitrate reducing and denitrifying bacteria concentrations ranged from less than the detection limit of 5 to greater than 2,400,000 MPN per gram of alluvium (Fig. 4). In general, nitrate reducing bacteria were more abundant than denitrifying bacteria regardless of overlying land use.

Median nitrate reducing bacterial abundance was not statistically different in the unsaturated zone beneath unsewered sites (overall median of JTUZ-1, JTUZ-2, and YVUZ-2 sites) compared to undeveloped sites, on the basis of the Median Test (Neter and Wasserman, 1974) with a confidence criterion of $\alpha = 0.05$ (Fig. 4).

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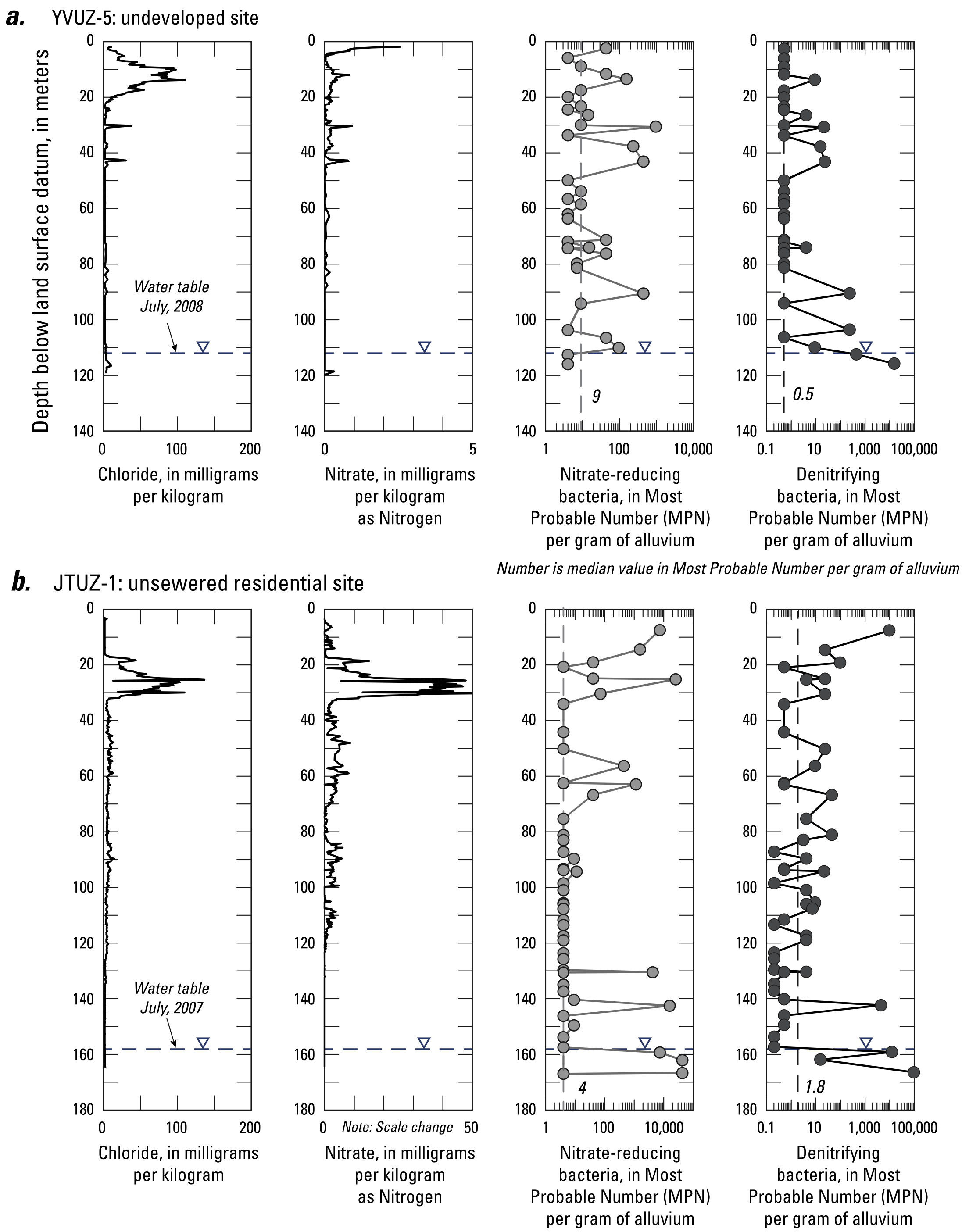

Fig. 3. Nitrate, chloride, nitrate reducing bacteria and denitrifying bacteria in unsaturated alluvium at YVUZ-5 and JTUZ-1, Warren Groundwater Subbasin, western Mojave Desert, California, July 2008 and July 2007, respectively.

Given the dry layers having low bacterial abundance at the JTUZ-1 site, the lack of a statistically significant difference is not surprising. However, nitrate reducing bacteria were more abundant at the comparatively moist JTUZ-2 site adjacent to a residential septic system, and at the EM-2 site irrigated with dairy wastewater (Fig. 4). Median denitrifying bacteria abundance beneath unsewered land use was statistically greater than beneath undeveloped land use on the basis of the Median Test (Neter and Wasserman, 1974) with a confidence criterion of $\alpha = 0.05$. Similar to nitrate reducing bacteria, denitrifying bacteria were more abundant at the JTUZ-2 and EM-2 sites.

Both types of bacteria were commonly occurring and widespread within unsaturated alluvium regardless of land use; however, they were not ubiquitous and often were below the reporting limit within thick, dry intervals underlying undeveloped, and unsewered land uses (Fig. 3). Nitrate reducing and denitrifying bacteria from undeveloped sites co-occur within a limited range in the unsaturated zone compared to unsewered and dairy wastewater land use (Fig. 5). Nitrate reducing or denitrifying bacteria abundance, but not necessarily both types of bacteria, commonly increased at unsewered or dairy wastewater irrigated sites (Fig. 5), suggesting nitrate reduction and denitrification do not

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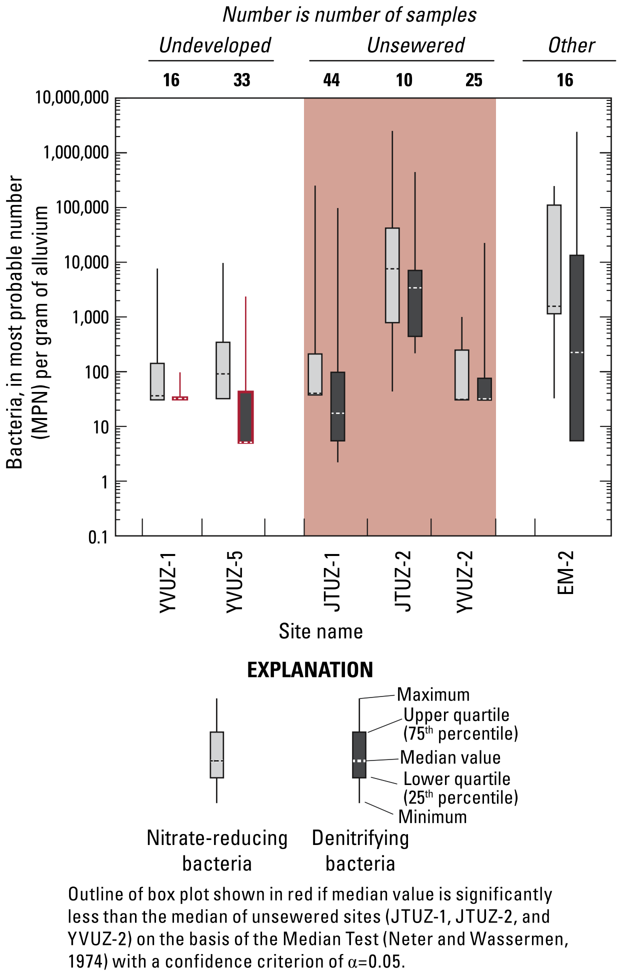

Fig. 4. Box plots showing nitrate reducing and denitrifying bacteria concentrations in the unsaturated zone beneath undeveloped, unsewered, and other land uses, Warren, Joshua Tree, and El Mirage Valley Groundwater Subbasins, western Mojave Desert, California, 2006–2008.

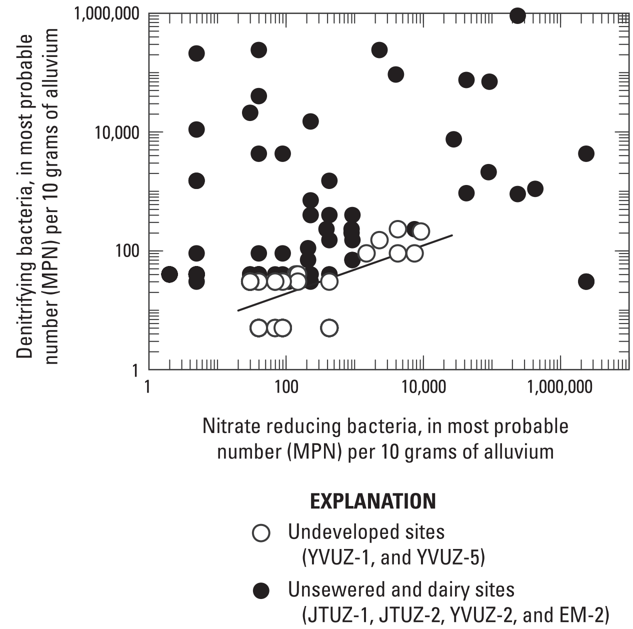

Fig. 5. Denitrifying bacteria concentrations as a function of nitrate reducing bacteria concentrations in the unsaturated zone beneath undeveloped, unsewered and dairy wastewater irrigated sites, Warren, Joshua Tree, and El Mirage Valley Groundwater Subbasins, western Mojave Desert, California, 2004–2008.

upper 30 m below the unsewered commercial land use. The number of amplicons increased as the number of nitrate reducing microorganisms increased but was not correlated with increases in the number of denitrifying microorganisms (Fig. 6).

These data suggest that there are a larger number of different types of microorganisms that can reduce nitrate, but fewer types of microorganism that can denitrify nitrate present within the unsaturated zone at these sites. Because these microorganisms are so widespread and occur at undeveloped sites, their simple presence does not necessarily mean nitrate reduction or necessarily co-occur and that at specific depths at individual sites one processes or the other dominates.

At sites where data from the saturated zone were available, nitrate reducing and denitrifying bacteria abundance increase below the water table regardless of land use (not shown in Figs. 3, 4, or 5), possibly reflecting lower oxygen concentrations in the saturated zone compared to the unsaturated zone.

Genetic material from microorganisms cultured in nutrient broth used for nitrate reducing and denitrifying bacteria was analyzed using Terminal-Restriction Fragment Length Polymorphism (T-RLFP) to evaluate differences in the diversity and microbial community structure at an undeveloped (YVUZ-1) and an unsewered site (YVUZ-2). Although only 10 samples from the two sites were analyzed, as many as 117 different amplicons, each representing at least one different microorganism, were identified. Each amplicon is composed of strands of ribosomal DNA (deoxyribonucleic acid) having different numbers of base pairs, isolated from the 500 base-pair long hypervariable region of the 16S rRNA gene using restriction enzymes and amplified using PCR (Polymerase Chain Reaction). The number of amplicons in individual cultures ranged from 9 to 38. Virtually all the amplicons in the unsaturated zone underlying undeveloped land use (YVUZ-1) also were present in the unsaturated zone underlying unsewered land use (YVUZ-2). Amplicons were present at YVUZ-2 that were not present at YVUZ-1. The number and diversity of microorganisms were greater in the

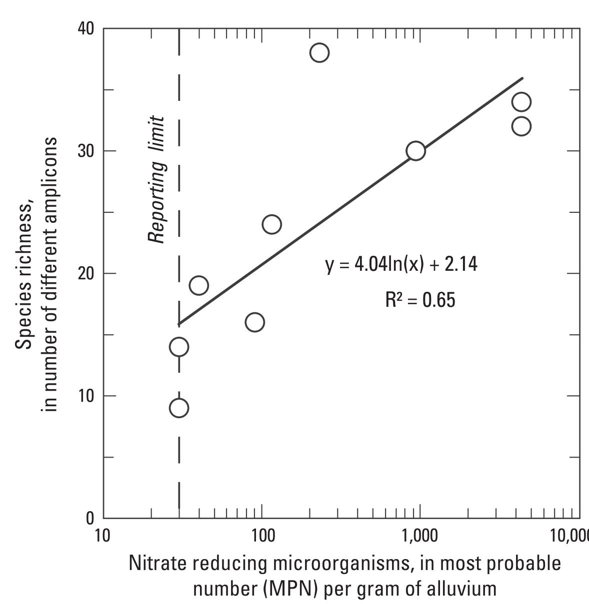

Fig. 6. Species richness as a function of nitrate reducing bacteria abundance in the unsaturated zone for undeveloped (YVUZ-1) and unsewered (YVUZ-2) land use, Warren Groundwater Subbasin, western Mojave Desert, California, September 2004.

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denitrification occur to any great extent, and additional chemical or isotopic data are needed to confirm if these processes are occurring within the unsaturated zone.

4.4. Water chemistry

Water samples were collected from septic tanks, public-supply wells, water-table monitoring wells, and suction-cup lysimeters installed in the unsaturated zone. Although not all data are discussed in this paper, data are available from the U.S. Geological Survey online database NWIS Web at waterdata.usgs.gov/nwis.

4.4.1. Septic effluent

Two samples were collected from within the commercial septic tank near YVUZ-2, and two samples were collected from the residential septic tank adjacent to JTUZ-2. Ammonia was the primary form of nitrogen in samples collected within septic tanks as part of this study. Ammonia concentrations ranged from 42 to 55 milligrams per liter as N, total nitrogen concentrations ranged from 49 to 60 mg/L as N. Ammonia concentrations were about 8% lower in residential septic effluent compared to commercial effluent. Ammonia composed about 91% of the total nitrogen in the commercial effluent and 87% in the residential effluent. The composition of samples collected within septic tanks as part of this study\was consistent with the literature values (Wakida and Lerner, 2005; Hinkle et al., 2008; Izbicki, 2014) and samples from septic tanks collected elsewhere in the Mojave Desert by Umari et al. (1993).

Ammonia and organic forms of nitrogen are converted to nitrate through bacterially mediated nitrification after discharge from the septic tank. Assuming complete conversion of ammonia and organic nitrogen to nitrate, nitrate concentrations from septic discharges would range from 49 to 60 mg/L as N with an average concentration of 54 mg/L as N. $\delta^{15}N–NO_3$ data discussed later in this paper suggest that small losses of nitrogen as ammonia occur as a result of sorption, or volatilization of ammonia or nitrous oxides during nitrification.

4.4.2. Suction-cup lysimeter and water-table well data

More than 250 samples were collected from suction-cup lysimeters in the unsaturated zone at nine sites underlying undeveloped, unsewered, and other (including irrigation with dairy wastewater and golf course) land uses between January 2005 and April, 2014. Nitrate was the primary form of nitrogen in samples collected from suction-cup lysimeters in the unsaturated zone, with smaller amounts of nitrite present (Table S1).

Most lysimeters at sites underlying undeveloped land uses did not yield water until after water infiltrated from recharge ponds (YVUZ-1 and YVUZ-5), or irrigation with dairy wastewater (EM-3) penetrated the unsaturated zone. The exceptions were lysimeters near the water table (YVUZ-1 at 88.8, YVUZ-1 at 95.9, YVUZ-5 at 89, and YVUZ-5 at 112.2). Median nitrate concentration in suction cup lysimeters from the undeveloped sites (YVUZ-1 and YVUZ-5) were significantly lower than median nitrate concentrations in lysimeters from unsewered sites (JTUZ-1, JTUZ-2, and YVUZ-2) on the basis of the Median Test (Neter and Wasserman, 1974) with a confidence criterion of $\alpha = 0.05$ (Fig. 7). There were no significant differences in median nitrate or nitrite concentrations between the unsewered sites and the dairy wastewater irrigated site (EM-2) or the former golf course site (YVUZ-3) on the basis of the Median Test (Neter and Wasserman, 1974) with a confidence criterion of $\alpha = 0.05$ (Fig. 7).

Between June 7, 2006 and October 29, 2007 approximately 6.4×10^6 m^3 of imported water was infiltrated from three ponds constructed at the YVUZ-1 site. Surface infiltration rates from the ponds were as high as 2.8 m/d, and downward movement of water

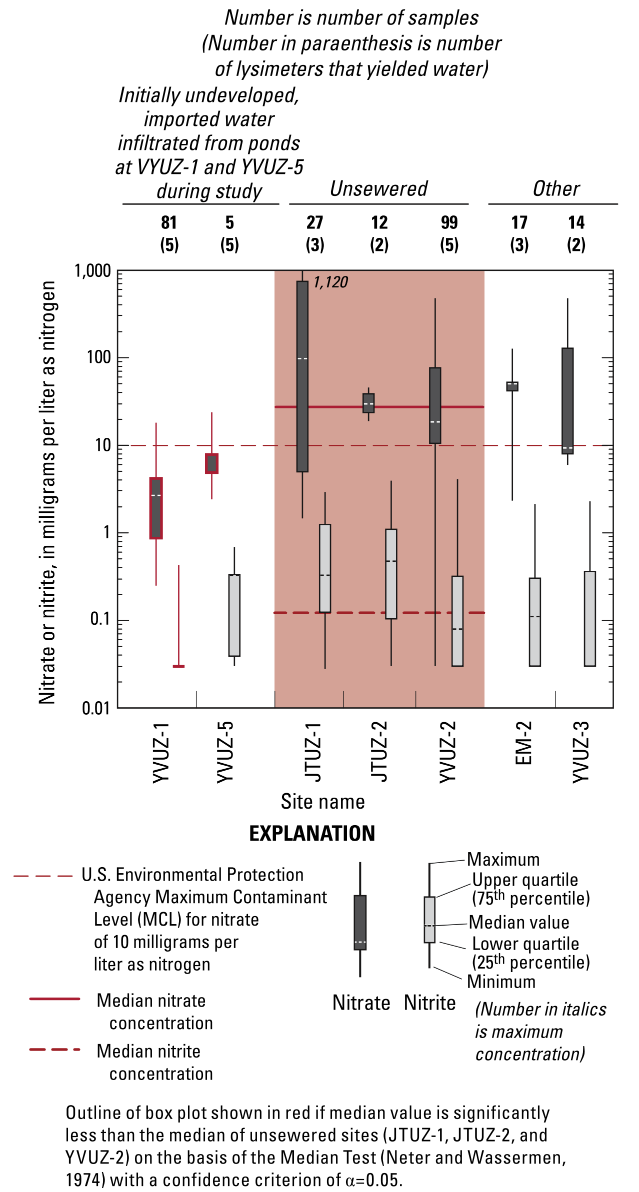

Fig. 7. Nitrate and nitrite concentrations in suction-cup lysimeters within the unsaturated zone at undeveloped, unsewered, and other land uses, Warren, Joshua Tree, and El Mirage Valley Groundwater Subbasins, western Mojave Desert, California, 2005–2014.

through the unsaturated zone was as high as 7.5 m/d (Stamos et al., 2013). Water infiltrated to a depth of 88 m within 28 days and arrived at the water table 100 m below land surface within 195 days after the onset of infiltration (Fig. 8). Nitrate concentrations declined as recharge progressed to values typically less than 2 mg/L as N, and ultimately approached concentrations similar to those in imported water of <1 mg/L as N (Fig. 9; Table S3). Nitrate concentrations in the water-table well at this site decreased from as high as 4 mg/L as N to less than 1 mg/L as N (Table S1). Although surrounded by the three ponds, YVUZ-1 was between 20 and 50 m from the ponds. Little lateral spreading occurred in the upper part of the unsaturated zone at the YVUZ-1 site, adjacent to recharge ponds, and infiltrated water did not reach the lysimeter at 29.7 m depth until April 2007, 5 months after the water reached the water table (Fig. 8). Nitrate concentrations at this depth remained relatively high compared to imported water, ranging from 6 to 18 mg/L as N, as a result of mobilization of natural nitrate within the shallow unsaturated zone.

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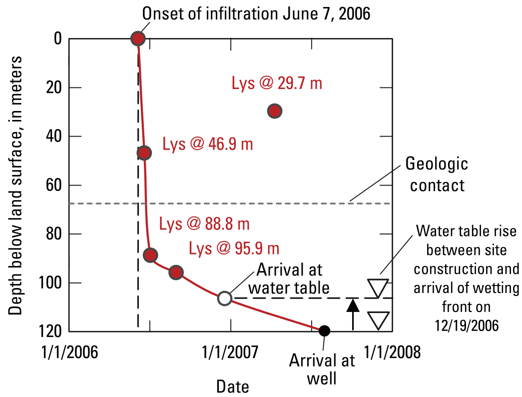

Fig. 8. Arrival of water at suction-cup lysimeter, the water table after infiltration from ponds at YVUZ-1, Warren Groundwater Subbasin, western Mojave Desert, southern California, 2006–2008.

Between November 12, 2008 and June 16, 2009, approximately 38,600 m^3 of local groundwater was infiltrated from a 0.06 ha pond constructed at YVUZ-5 to characterize the potential for future infiltration of treated municipal wastewater at the site. Surface infiltration rates were as high as 1.9 m/d, and water reached the water table 112.8 m below land surface March 26, 2009, 114 days after the onset of infiltration. Nitrate concentrations in samples from lysimeters ranged from 2.1 to 24 mg/L as N (Fig. 7). Nitrate concentrations increased with depth as nitrate and other soluble salts were mobilized from the unsaturated zone by the infiltrating water. Nitrate concentrations exceeded the MCL of 10 mg/L as N in the deepest lysimeter 112.2 m below land surface as a result of mobilization of naturally-occurring nitrate within the unsaturated zone by infiltrating water. Nitrate concentrations in the water-table well at this site increased from 0.6 to 2.5 mg/L as N after infiltrated water reached the water table as a result of mobilization of naturally-occurring nitrate from the unsaturated zone. Presumably nitrate concentrations would have declined with time, similar to JTUZ-1 and other sites in the Mojave Desert (Izbicki et al., 2008), if infiltration of water at this site had continued.

In contrast to sites where recharge from ponds occurred, the unsaturated zones underlying unsewered land use (JTUZ-1, JUTZ-2 and YVUZ-2) were sufficiently moist that most suction-cup lysimeters yielded water soon after the sites were installed. However, unsaturated deposits at JTUZ-1 were highly-layered, composed of alternately moist and dry material, and some depths were dry and did not yield water to lysimeters during this study. Median nitrate concentrations at JTUZ-1, JTUZ-2 and YVUZ-2 were 97, 30, and 18 mg/L as N, respectively, and exceeded the MCL for nitrate of 10 mg/L as N (Fig. 7). Median nitrite concentrations at these sites were 0.33, 0.45, and 0.08 mg/L as N, respectively. Maximum nitrite concentrations of 2.9, 4.0, and 4.1 mg/L as N are consistent with nitrate reduction within the unsaturated zone.

The smallest range in nitrate concentrations, 19–46 mg/L as N (Fig. 6; Table S1), was from the lysimeters at the JTUZ-2, adjacent to a residential septic system. These concentrations were slightly lower than nitrate concentrations expected from complete nitrification of ammonia in septic systems sampled as part of this study, and were consistent with nitrogen losses through sorption or volatilization of ammonia, incorporation into microbial biomass, nitrate reduction, or denitrification.

In contrast to JTUZ-2, nitrate concentrations from suction cup lysimeters at JTUZ-1 ranged from 1.5 to 1,120 mg/L as N (Table S2). Nitrate concentrations from lysimeters at 27.3 and 105.5 m below land surface exceeded 87 mg/L as N, and were greater than the concentrations expected from sampled septic systems. Very high nitrate concentrations in excess of 100 mg/L as N

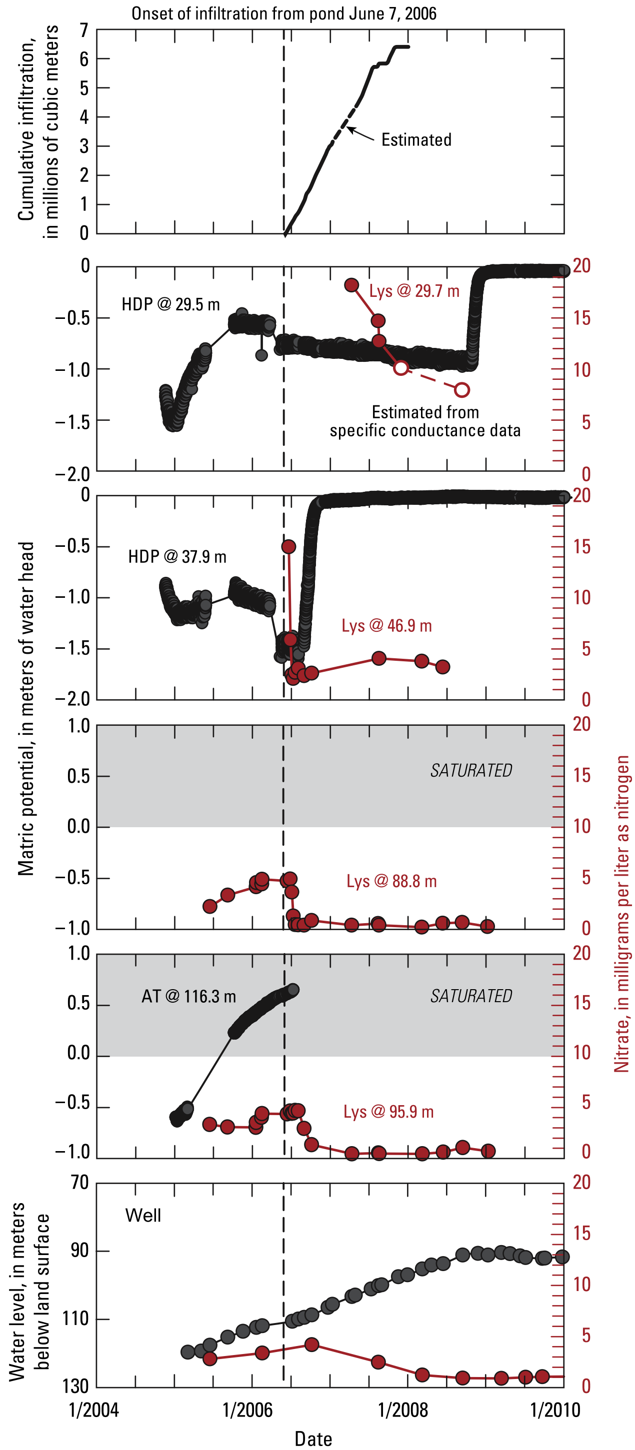

Fig. 9. Water level, matric potential, and nitrate concentration data at site YVUZ-1 before and after infiltration from ponds, Warren Groundwater Subbasin, western Mojave Desert, southern California.

were associated with low-volume, high specific conductance samples indicative of low moisture contents and extensive interaction with soluble salts with the unsaturated zone. Low nitrate concentrations, ranging from 1.5 to 5.7 mg/L as N, consistent with natural or slightly elevated nitrate concentrations, were measured at 154.7 m below land surface, just above the water table 158 m below land surface. However, nitrate concentrations in the water table well at JTUZ-1 ranged from 12 to 14 mg/L as N and exceeded the MCL of 10 mg/L as N. Although elevated nitrate concentrations are consistent with the arrival of water from nearby septic discharges at the water table, data from YVUZ-5 suggest that mobilization of naturally-occurring nitrate from the unsaturated zone also can contribute elevated nitrate to the water table. Stable nitrogen and oxygen isotopes in nitrate (discussed later in this paper) were used to identify nitrate contributions from natural and septic sources.

Nitrate concentrations in lysimeters at YVUZ-2 ranged from 0.19 to 480 mg/L as N. Nitrate concentrations in lysimeters from shallower depths in YVUZ-2 above 83.2 m (Table S2) were commonly in excess of the MCL of 10 mg/L as N. Similar to JTUZ-1, very high nitrate concentrations at this site also were associated with low-volume, high specific conductance samples indicative of low moisture contents. Nitrate concentrations in the lysimeter at 100.9 m, just above the water table at 102.8 m below land surface, were low ranging from 0.15 to 2.5 mg/L as N and consistent with natural concentrations. Nitrate concentrations in the water table well at this site ranged from 2.0 to 2.4 mg/L as N, within the range of natural concentrations (Mueller and Helsel, 1996; Dwivedi et al., 2007), and indicate that nearby septic discharges have not reached the water table at this site. Between 2005 and 2008 the water table at the YVUZ-2 site rose more than 30 m as a result of recharge with imported water elsewhere in the subbasin (Stamos et al., 2013), submerging lysimeters at 100.9 and 82.3 m below land surface (Fig. 10). As the water table rose, nitrate in the unsaturated zone was entrained in the rising groundwater and nitrate concentrations as high as 58 mg/L as N were measured in the lysimeter at 83.2 m as the water table reached this depth. Nitrate subsequently decreased to lower concentrations as the water table rose above this depth.

Nitrate concentrations in lysimeters at the EM-2 and YVUZ-3 sites ranged from 2.3 to 130 and 6 to 510 mg/L as N respectively (Fig. 7; Table S2). Nitrate concentrations ranging from 17 to 53 mg/L as N (Table S2) also were measured at the EM-3 site as a consequence of irrigation with dairy wastewater after the site was constructed (not shown on Fig. 7). Maximum nitrite concentrations of 2.2 and 2.3 mg/L as N are consistent with nitrate reduction within the unsaturated zone at these sites.

4.5. Unsaturated zone gas compositions

Unsaturated zone gasses were sampled from gas samplers installed at the unsewered residential sites JTUZ-1 and JTUZ-2. Nitrogen, oxygen, and argon in the unsaturated zone at these sites were within ranges expected for atmospheric gasses (Table S2). Carbon dioxide concentrations were almost an order of magnitude greater than atmospheric concentrations; but were not unusual for unsaturated zone gasses, where bacteria respiration would be expected to consume oxygen and produce carbon dioxide. Nitrous oxide (N_2O), produced through reduction of nitrate by nitrate reducing bacteria, was detected at low concentrations at both the JTUZ-1 and JTUZ-2 sites (although analysis of replicate samples from depths where N_2O was detected produced inconsistent results.) Detections were more frequent at the JTUZ-2 site adjacent to an active septic system than at the JYUZ-1 site. The detection at JTUZ-1 was from 27.4 m below land surface at the depth of the highest nitrate concentrations and highest nitrate reducing bacteria abundance. The data are consistent with the presence of nitrite that indicates some nitrate reduction may occur in the unsaturated zone.

4.6. Stable isotope ratios in ammonia and nitrate

The stable isotope ratios of nitrogen in ammonia ($\delta^{15}N–NH_4$) and nitrate ($\delta^{15}N–NO_3$) and the stable isotopic ratio of oxygen in nitrate ($\delta^{18}O–NO_3$) were measured in water samples from suction-cup lysimeters, monitoring wells, and selected production wells to evaluate to source of nitrate and the processes that control the movement and occurrence of nitrate in alluvial aquifers in arid areas underlying selected land uses. Previously collected $\delta^{15}N–NO_3$ data from water extractions from alluvium, public-supply and monitoring wells the study area (Nishikawa et al., 2003) also were evaluated with data collected as part of this study.

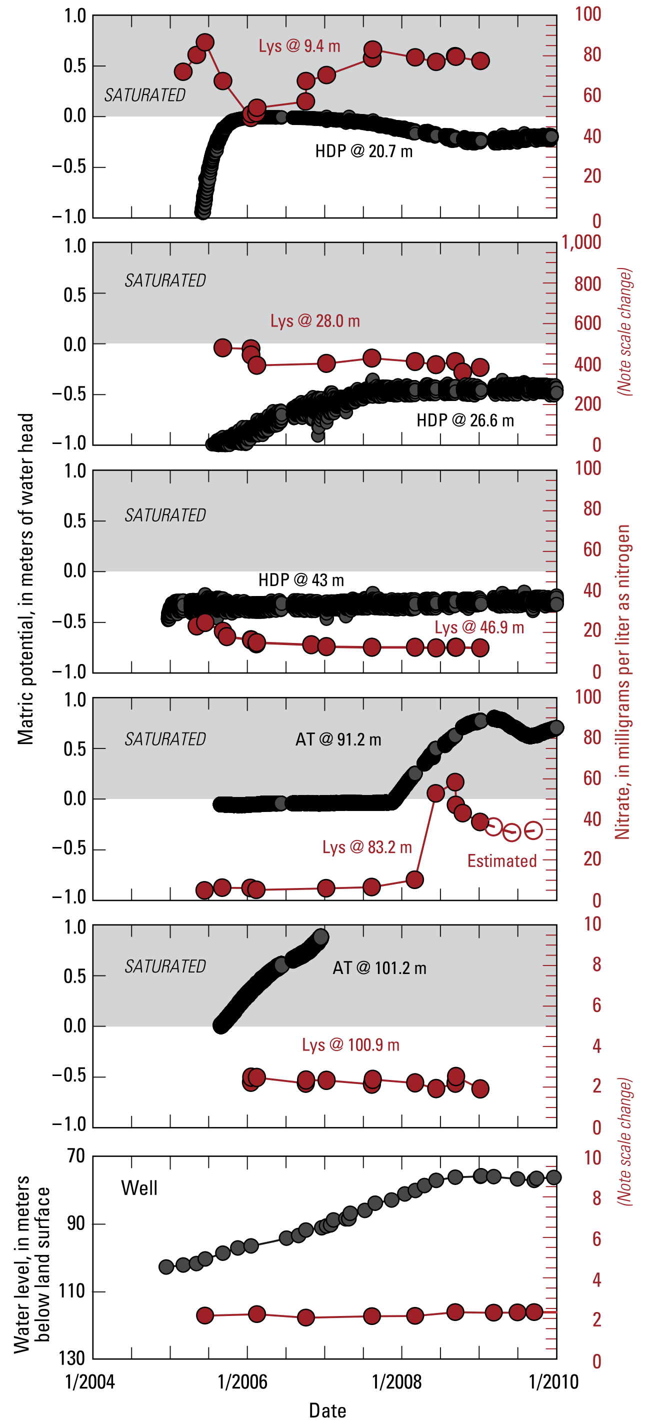

Fig. 10. Water level, matric potential, and nitrate concentration data at site YVUZ-2, Warren Groundwater Subbasin, western Mojave Desert, southern California, 2004–2010.

4.6.1. Stable nitrogen isotope ratios in ammonia and nitrate

Septic tanks were sampled at the YVUZ-2 and JTUZ-2 sites. The septic tank at the YVUZ-2 site served a commercial building and the septic tank at the JTUZ-2 sites served a residential home. The $\delta^{15}N$ compositions of ammonia in water from the commercial and residential septic tank were 5.1 and 4.9 per mil, respectively. The difference between commercial and residential samples was not analytically significant; and data from the sites were consistent with the literature values (Wakida and Lerner, 2005; Hinkle et al., 2008) and with samples from septic tanks collected elsewhere in the Mojave Desert (Umari et al., 1993).

$\delta^{15}N$–NO_3 values in water from almost 50 samples from public-supply wells, multiple-well monitoring sites, and water-table wells in the Warren and Joshua Tree Subbasins sampled as part of this study and as part of previous work (Nishikawa et al., 2003) ranged from 0.19 to 11.6 per mil (Table S3) with a median value of 6.7 per mil. The median nitrate concentration in water from these wells was 4.4 mg/L as N, and the maximum concentration was as high as 28 mg/L as N. $\delta^{15}N$–NO_3 values in water in 21 samples from 15 suction-cup lysimeters in the unsaturated zone beneath natural and unsewered sites ranged from 5.0 to 20.3 per mil with a median value of 7.9 per mil (Table S3). The median nitrate concentration in these samples was 7.9 mg/L as N and the maximum concentration was as high as 1,040 mg/L as N. Nitrate concentrations and $\delta^{15}N$–NO_3 values in water from wells and suction-cup lysimeters in the unsaturated zone are affected by mixing of septic effluent with native water containing naturally-occurring nitrate from alluvium, and by nitrate reduction and denitrification. $\delta^{15}N$–NO_3 values shift to increasingly larger (heavier) values as nitrate is reduced to nitrate or converted to nitrogen gas and removed through denitrification.

Mixing models were developed to evaluate contributions from septic and naturally-occurring nitrate in the saturated and unsaturated zone; the models also incorporate the effect of denitrification on nitrate concentrations and $\delta^{15}N$–NO_3 compositions (Fig. 11). The upper mixing curve represents simple mixing of septic water having a nitrate concentration of 50 mg/L as N and a $\delta^{15}N$–NO_3 value of 7.2 per mil with native groundwater having a nitrate concentration of 2 mg/L as N and a $\delta^{15}N$ value of 5.4 per mil. The native groundwater nitrate concentration is within the range of nitrate concentrations in native water estimated by Mueller and Helsel (1996) and Dwivedi et al. (2007). The native groundwater $\delta^{15}N$ value for the upper curve is the average composition of nitrate measured in water extractions from alluvium in the study area (Nishikawa et al., 2003). The lower mixing curve represents mixing of septic water with native water having the same nitrate concentration as the upper curve, and a $\delta^{15}N$ value of 0 per mil. The near-zero $\delta^{15}N$–NO_3 value represents nitrate in native groundwater derived infiltration of streamflow from Water Canyon. A nitrate concentration of 50 mg/L as N and a $\delta^{15}N$–NO_3 value of 7.2 per mil were used for the septic end member of both mixing lines. These values are consistent with literature values for nitrate (Umari et al., 1993; Wakida and Lerner, 2005) and $\delta^{15}N$–NO_3 (Hinkle et al., 2008) derived from septic sources. The $\delta^{15}N$–NO_3 value for septic nitrate is slightly heavier than the average $\delta^{15}N$ composition of ammonia measured in the sampled septic systems of 5.0 per mil, and consistent with a small loss of nitrogen during conversion of ammonia to nitrate similar to data measured in lysimeters at JTUZ-2 adjacent to a residential septic system. The extent of denitrification was estimated as departure from the upper mixing line for various mixing fractions (Fig. 11) as a Rayleigh process, assuming a constant fractionation factor of $\varepsilon = -29.4$ (Mariotti et al., 1981).

Although simplified with respect to the ranges in septic effluent and soil nitrate, the mixing lines and denitrification trend lines shown in Fig. 11 provide an adequate fit to measured data and a

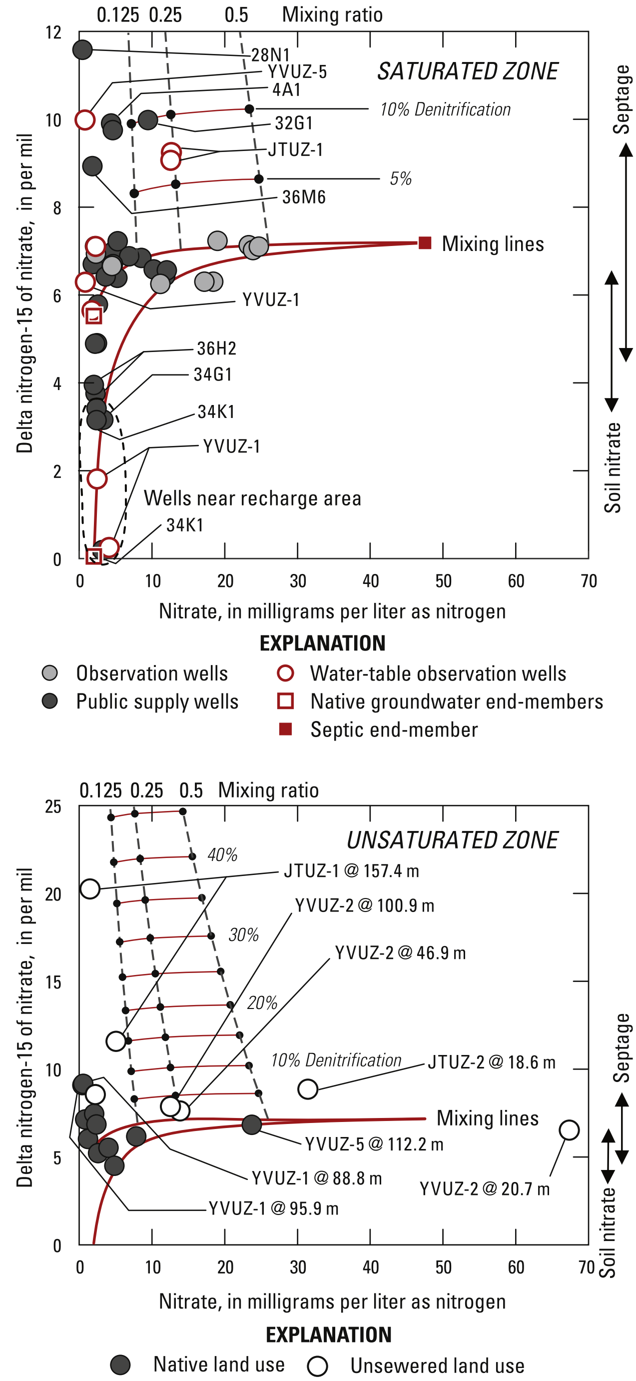

Fig. 11. delta Nitrogen-15 of nitrate ($\delta^{15}N$–NO_3) as a function of nitrate concentration in water from (A) saturated and unsaturated zone, Warren, and Joshua Tree Groundwater Subbasins western Mojave Desert, California, 2004–2008.

framework to discuss nitrate sources and processes occurring in the study area. This simplified approach is useful in the Warren subbasin and Joshua Tree areas because most of the nitrate in these areas is derived from septic discharges or natural sources. The approach would be less useful in areas having a wider range of nitrate sources from chemical fertilizer or animal manures having a wider range of nitrate concentrations and $\delta^{15}N$–NO_3 values.

Water from most public-supply wells and observation wells (Nishikawa et al., 2003) plot near or between the two mixing lines (Fig. 11A) and could be explained by mixing a native groundwater with septic effluent with little (<5%) denitrification. Using this simple model it is difficult to distinguish nitrate from septic and natural sources, other than near Water Canyon. Heavier $\delta^{15}N–NO_3$ values in water from wells 28N1, 4A1, 32G1, and 36M6 (Fig. 11, Table S3), may have been affected by as much as 5–15% denitrification of the initial nitrate (Fig. 11A). Nitrate and $\delta^{15}N–NO_3$ values consistent with about 7% denitrification also were present in the water table well at the unsewered residential JTUZ-1 site (Fig. 11). In contrast, low nitrate concentrations and light $\delta^{15}N–NO_3$ values in water from the water-table well at YVUZ-1 (Fig. 11) reflect the composition of water infiltrated from streamflow near the site prior to pond construction. Nitrate concentrations decreased and $\delta^{15}N–NO_3$ values increased from 0.25 to 6.3 per mil (Table S3) as imported water (having a $\delta^{15}N–NO_3$ value of 9.7 per mil, Table S2) was recharged and infiltrated to the water table at the site. $\delta^{15}N–NO_3$ values in water from nearby wells 34K1 and 34G1 collected prior to infiltration of imported water (Nishikawa et al., 2003) also were comparatively light (Fig. 11) and reflect contributions of nitrate in water infiltrated from streamflow.

The two mixing lines in Fig. 11 closely bound most data from suction-cup lysimeters in the unsaturated zone underlying undeveloped land used for groundwater recharge (Fig. 11B). The extent of denitrification at these sites, typically less than 5%, was similar to the extent of denitrification estimated in wells (Fig. 11A). Similar to changes in $\delta^{15}N–NO_3$ values observed in the water table well at YVUZ-1, increasingly heavy $\delta^{15}N–NO_3$ values were found in lysimeters at YVUV-1, 95.9 m and 88.3 m below land surface, as infiltration from ponds occurred and reflect mixing with imported water (Fig. 11B, Table S3). In contrast, water from the lysimeter 18.6 m below land surface at JTUZ-2, adjacent to a residential septic system, contained more than 60% nitrate from septic sources, although only a small amount of denitrification (<5%) occurred (Fig. 11B). Similarly, as much as 25% nitrate from septic effluent with little denitrification also was present in water from lysimeters at YVUZ-2 at 100.9 and 46.9 m below land surface, receiving commercial septic effluent. Nitrate in water from two samples from the lysimeter 157.3 m below land surface at the JTUZ-1 site had heavy $\delta^{15}N$ compositions, suggesting 15 to almost 40% of the original nitrate was lost through denitrification. Denitrification may partly explain the low concentrations in the unsaturated zone at this depth, while nitrate concentrations in the water-table a few meters below exceeded the MCL of 10 mg/L as N. $\delta^{15}N–NO_3$ values in water from water table wells and lysimeters at the sites receiving dairy wastewater, EM-2 and EM-3, were among the heaviest measured as part of this study, ranging from 12 to 18 per mil (Table S3). These values are not shown in Fig. 11 because they do not have a septic source of nitrate. Although denitrification is likely at this site, given variability in $\delta^{15}N–NO_3$ from animal manure sources of 8–20 per mil (Fogg et al., 1998), it is not possible to quantify the extent of denitrification. $\delta^{18}O–NO_3$ data were used to evaluate the extent of denitrification at the EM-2 and EM-3 sites receiving dairy wastewater, and the YVUZ-3 (golf course) site.

On the basis of nitrate and $\delta^{15}N–NO_3$ data, mixing and subsequent dilution is the primary mechanism for attenuation of nitrate concentrations in the study area. This is consistent with previous work in the study area that documented a rapid rise in nitrate concentrations from entrainment of septic wastewater after a rapid rise in water levels resulting from groundwater recharge with imported water (Nishikawa et al., 2003).

4.6.2. Oxygen isotopes of nitrate

$\delta^{18}O–NO_3$ values in 18 samples from public-supply wells, and water-table observation wells ranged from −3.7 to 8.2 per mil, with a median value of 0.93 per mil (Table S3). In contrast, $\delta^{18}O–NO_3$ values in water from wells in the alluvial aquifer underlying the Malibu area, where extensive denitrification of septic effluent

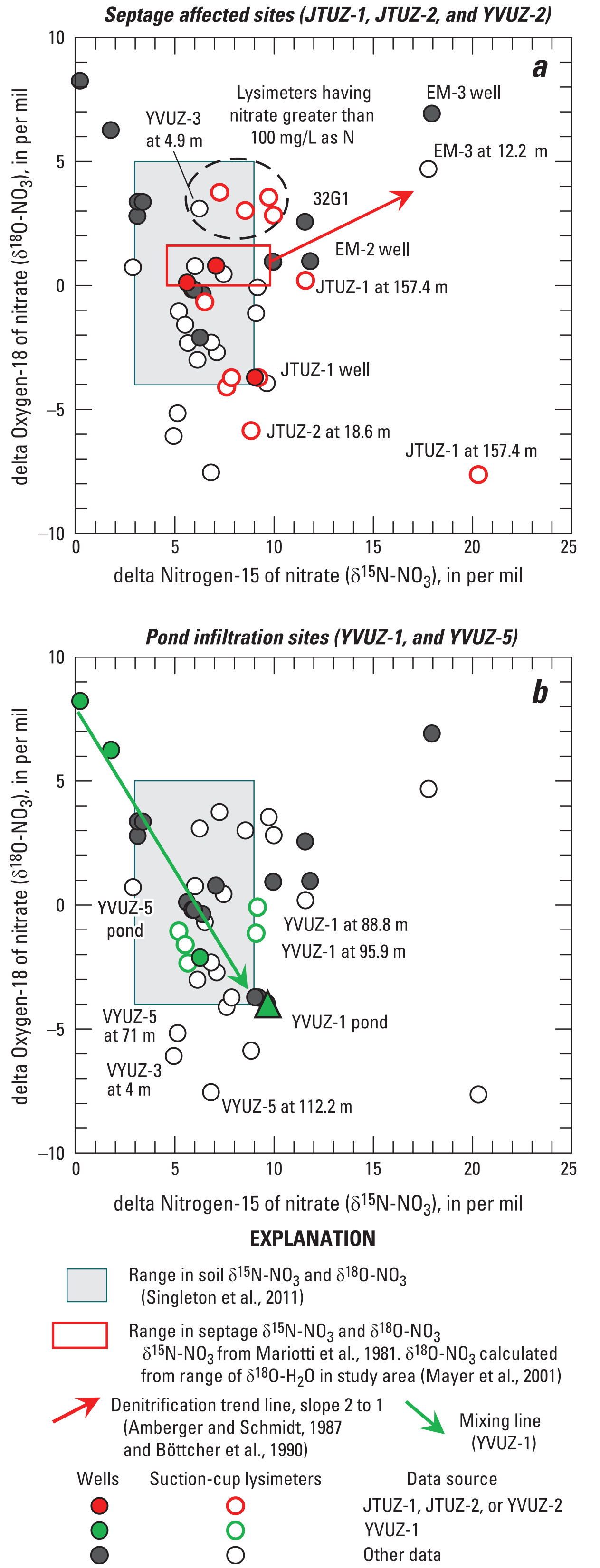

Fig. 12. delta Oxygen-18 of nitrate ($\delta^{18}O–NO_3$) as a function of delta nitrogen-15 nitrate ($\delta^{15}N–NO_3$) from wells and suction-cup lysimeters at unsewered and dairy wastewater irrigated sites, Warren, Joshua Tree, and El Mirage Valley Groundwater Subbasins, western Mojave Desert, southern California 2006–2009.

occurred, ranged from 0.9 to 20 per mil (Izbicki, 2014). Many of the production wells previously sampled and analyzed for $\delta^{15}N–$

NO_3 by Nishikawa et al. (2003) were not analyzed for $\delta^{18}O–NO_3$ because the technique is comparatively new and was not available during the previous study. $\delta^{18}O–NO_3$ values from 25 samples from lysimeters in the unsaturated zone ranged from −7.6 to 4.7 per mil, with a median value of −1.1 per mil (Table S3).

The range in $\delta^{15}N–NO_3$ and $\delta^{18}O–NO_3$ values was greater than the range in septic $\delta^{15}N–NO_3$ from Hinkle et al. (2008) and the calculated range for $\delta^{18}O–NO_3$ in septic effluent (assuming two-thirds of the oxygen in nitrate originated from hydrolysis of local water and one-third from atmospheric oxygen, Mayer et al., 2001) (Fig. 12). More positive $\delta^{18}O–NO_3$ values may occur during nitrification of ammonia if plant or microbiological respiration increased the isotopic composition of oxygen in the unsaturated zone to heavier than atmospheric values of 23.5 per mil (Snider et al., 2010). The range in $\delta^{15}N–NO_3$ and $\delta^{18}O–NO_3$ values also was greater than the range in $\delta^{15}N–NO_3$ from soil and alluvial extractions in the study area (Nishikawa et al., 2003), and the range in $\delta^{18}O–NO_3$ from soil and alluvium elsewhere in California (Singleton et al., 2011). More negative $\delta^{18}O–NO_3$ values suggest contributions from soil or alluvium having lighter values than those reported by (Singleton et al., 2011). Denitrification is indicated as shifts in the $\delta^{15}N–NO_3$ and $\delta^{18}O–NO_3$ composition along a line having a slope of 2–1, respectively (Amberger and Schmidt, 1987; Böttcher et al., 1990).

High $\delta^{18}O–NO_3$ and low $\delta^{15}N–NO_3$ values were measured in water from the water-table observation well at YVUZ-1 (Fig. 12) in the western part of the Warren subbasin prior to the arrival of imported water infiltrated from ponds at the site. These values were consistent with nitrate derived from fertilizer or atmospheric sources (Choi et al., 2003), fall outside the range of $\delta^{18}O–NO_3$ in soil and alluvium (Singleton et al., 2011), and may represent nitrate derived from infiltration of stormflow from Water Canyon that had limited interaction with soil nitrate. Similar high values also were measured in nearby public-supply wells, 34K2 and 34Q1. The $\delta^{18}O–NO_3$ and $\delta^{15}N–NO_3$ composition of water from YVUZ-1 shifted to lighter $\delta^{18}O–NO_3$ values and heavier $\delta^{15}N–NO_3$ values after imported water infiltrated from ponds at the site reached the water table (Fig. 12B). A similar shift to lighter $\delta^{18}O–NO_3$ and heavier $\delta^{15}N–NO_3$ values also occurred as a result of infiltration of local groundwater at the YVUZ-5 site (Table S3). The change in the isotopic composition of water during recharge from lysimeters at YVUZ-5 is consistent with nitrate contributions from alluvium and suggests the $\delta^{18}O–NO_3$ composition within the unsaturated zone in the study area may be about −8 per mil, and lighter than values reported by Singleton et al. (2011).

Most data from water table wells and lysimeters at unsewered commercial and residential sites (YVUZ-2, JTUZ-1, and JTUZ-2) have $\delta^{18}O–NO_3$ values lighter than the expected composition of septic effluent (Fig. 12A). Assuming nitrification of ammonia under conditions postulated by Mayer et al. (2001) and Snider et al. (2010), these data show contributions of naturally-occurring nitrate in the unsaturated zone, similar to data from YVUZ-1 and YVUZ-5. Most samples show little or no shift in $\delta^{15}N–NO_3$ and $\delta^{18}O–NO_3$ compositions from denitrification (Fig. 12). However, $\delta^{15}N–NO_3$ and $\delta^{18}O–NO_3$ data from well 32G1 and from the lysimeter at JTUZ-1 at 157.4 m (collected 3/11/09, Table S3), previously identified as partly denitrified (Fig. 11), are consistent with about 10% denitrification. (The sample from JTUZ-1 at 157.4 m collected on 8/16/07, Table S3, had an unusual composition compared to all other samples and could be an artifact of drilling and lysimeter installation at the site.) Given a similar $\delta^{18}O$ composition of water, samples from the EM-3 well and the lysimeter at 12.2 m below land surface also show evidence of more than 30% denitrification (Fig. 12). Smaller amounts of denitrification also were evident in the water table well at EM-2.

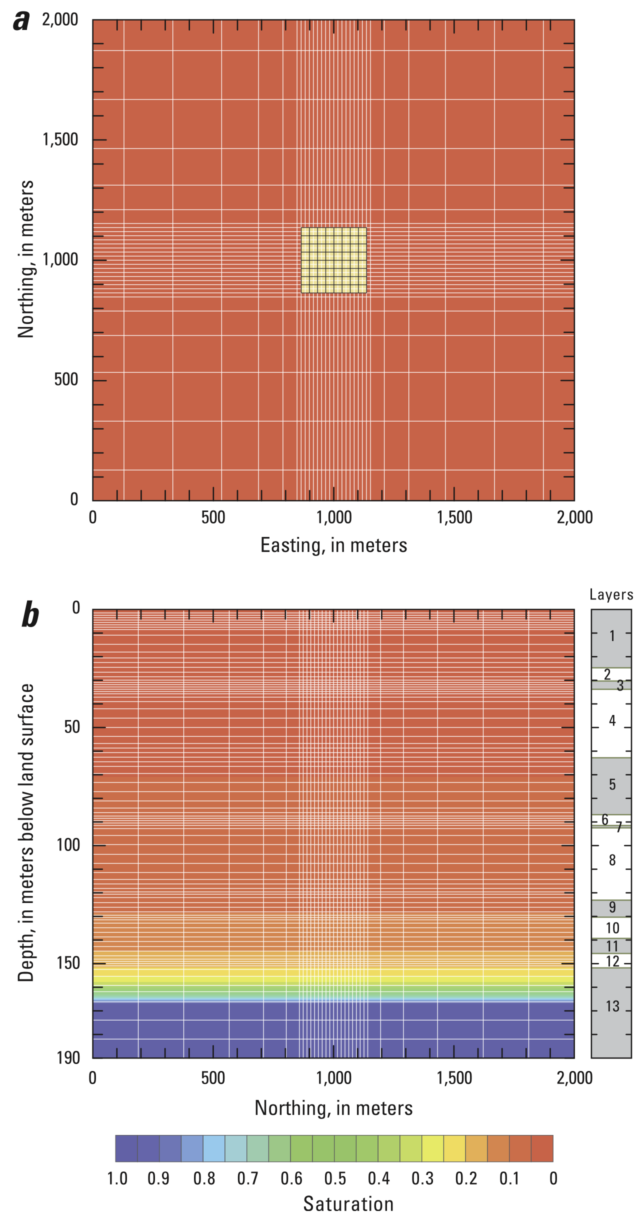

Fig. 13. Unsaturated-zone model grid showing (a) areal spatial discretization, (b) vertical discretization and layering, and initial saturation, Warren Groundwater Subbasin, western Mojave Desert, southern California.

In contrast to most data, water from lysimeters having high nitrate concentrations, greater than 100 mg/L as N (JTUZ-1 at 27.7 m and YVUZ-2 at 28 m; Table S3), have $\delta^{18}O–NO_3$ values heavier than the expected composition of septic effluent (Fig. 12A). The $\delta^{18}O–NO_3$ composition of these data may be consistent with nitrification of ammonia in septic effluent under low oxygen conditions (Mayer et al., 2001; Snider et al., 2010) and the small quantities of saline water yielded by these lysimeters during sample collection are consistent with small volumes of septic effluent impacted by soluble anions from unsaturated alluvium. Collectively high-nitrate samples from JTUZ-1 and YVUZ-2 represent a different combination of physical, chemical, and hydraulic processes operating on septic discharges than occurred in more rapidly draining effluent. The possible effect of layering on the lateral movement of septic effluent within the unsaturated zone that may have increased contact with alluvium and dissolution of soluble anions was evaluated using numerical models. High nitrate

Table 2
Texture and hydraulic properties of unsaturated-zone model layers, Joshua Tree Groundwater Subbasin, western Mojave Desert, California.

Model layer	Texture	Depth interval, in meters	Porosity, in meter	Saturated hydraulic conductivity, in meters per day	van Genuchten parameters	
					m	$1/\alpha$, in meters
1	Loamy Sand	0–24.7	0.37	0.58	0.6855	0.28
2	Sandy Loam	24.7–30.2	0.46	0.14	0.2019	0.67
3	Gravelly Sand	30.2–33.8	0.38	3.07	0.4309	0.27
4	Loamy Sand	33.8–62.8	0.49	0.50	0.4037	1.52
5	Sand	62.8–86.9	0.37	1.80	0.6855	0.28
6	Sandy Loam	86.9–91.5	0.38	0.10	0.2845	0.32
7	Gravelly Sand	91.5–92.5	0.39	1.80	0.5151	0.24
8	Sand	92.5–123.1	0.49	0.92	0.4037	1.52
9	Sandy Loam	123.1–130.3	0.38	1.54	0.6274	0.29
10	Sandy Loam	130.3–139.9	0.46	0.10	0.2019	0.67
11	Loamy Sand	139.9–145.7	0.49	0.33	0.4037	1.52
12	Sand	145.7–151.8	0.38	1.54	0.6274	0.29
13	Loamy Sand	151.8–190.0	0.37	0.65	0.6855	0.28
Uniform layer (special case analysis)			0.38	0.30	0.4309	0.27

Table 3
Unsaturated-zone model simulation results for 5 housing densities and three model-layer slopes for models with uniform and layered properties, Joshua Tree Groundwater Subbasin, western Mojave Desert.

Septic systems in 20 hectare development	Slope of model layers (°)	First arrival of water at water table, in years		Condition at water table at 100 years			
				Flux of water, in liters per day		Concentration of nitrate, in milligrams per liter as nitrogen	
		Uniform	Layered	Uniform	Layered	Uniform	Layered
1	0	>100	>100	0	0	2	2
	2.5	>100	>100	0	0	2	2
	5	>100	>100	0	0	2	2
4	0	85	>100	20	0	2	2
	2.5	85	>100	20	0	2	2
	5	85	>100	20	0	2	2
16	0	55	55	8700	9100	33	4
	2.5	55	95	8700	380	33	2
	5	55	95	8700	380	33	2
32	0	45	45	23,500	24,600	36	26
	2.5	45	45	23,500	14,000	36	27
	5	45	55	23,500	11,400	36	35
64	0	45	45	43,500	30,300	38	30
	2.5	45	45	43,500	29,100	38	32
	5	45	45	43,500	28,000	38	37

concentrations, and high $\delta^{15}N–NO_3$, and $\delta^{18}O–NO_3$ values also were measured underlying the formerly irrigated golf course in water from the lysimeter at YVUZ-3,12.8 m below land surface (Fig. 12A; Table S3).

5. Numerical model results

A conceptual model of water and nitrate movement through the unsaturated zone underlying unsewered residential development on alluvial fans along the southern edge of the Joshua Tree Groundwater Subbasin was developed on the basis of in situ borehole data (water potential and temperature), geophysical logs, and water chemistry from laboratory analysis of cuttings and core. This setting was selected for model analysis because, although it was known that septic discharges and associated nitrate had infiltrated through well-sorted alluvial deposits underlying older portions of the communities of Yucca Valley and Joshua Tree and reached the water table, it was not known if septic discharges and nitrate had infiltrated through layered, unsaturated alluvial fan deposits along the margin of the Groundwater Subbasins and reached the water table. The purpose of the model was to evaluate selected factors that influence (1) the travel time of septic leachate to the water table, (2) the nitrate concentration in the unsaturated zone and at the water table once leachate enters the saturated zone, and (3) the relative changes in flow rates and nitrate concentration when septic leachate is increased with the addition of houses. The model incorporates the effect of increased storage of septic discharges within the layered unsaturated zone and, consistent with chemical and isotopic data, does not include nitrate removal through denitrification.

5.1. Model development

The computer program, TOUGH2 (**T**ransport **O**f **U**nsaturated **G**roundwater and **H**eat), an integrated finite-difference numerical code (Pruess et al., 1999), was used to develop a conceptual three-dimensional numerical model of septic effluent movement through the unsaturated zone underlying unsewered residential development in Joshua Tree. TOUGH-2 simulates the flow of heat, air, water, and solutes (nitrate from septic tank discharges) in three dimensions under saturated and unsaturated conditions.

The model domain is 2000 m by 2000 m (400 ha), 200 m thick, and contains approximately 81,685 grid elements (Fig. 13). Areal grid spacing (x, y dimensions) within the model is variable, so that grid elements near the center of the model are approximately 223 m^2 (the approximate area of a typical leach field). This configuration allowed for simulation of as many as 64 approximately 0.1 ha parcels (the size of a typical residential lot) consisting of four grid elements (Fig. 13a)—enabling testing the effect of various housing densities and associated septic leach fields. For the purposes of the simulations, the leach field was always located in the same corner of the four-element parcel. Model grid spacing within the vertical (z dimension) was variable and ranged from 1 to 4 m (Fig. 13b). The bottom boundary of the model was 200 m and the water table was at 165-m depth. The upper model boundary was a standard atmospheric condition. The lateral boundaries of the model were no-flow boundaries.

5.2. Model properties

The model includes 13 alluvial layers having distinct hydraulic properties developed on the basis of lithologic (texture) and geophysical data from two boreholes (JTUZ-1 and JTUZ-2), and results from laboratory analysis of alluvium (Table 2). Hydraulic properties for the simulated layers were estimated from textural analysis of borehole cuttings and a neural network pedotransfer function using the computer program Rosetta (Schaap et al., 2001). The pedotransfer function uses the measured textural percentages to estimate porosity, saturated hydraulic conductivity, water retention parameters, alpha and n (van Genuchten, 1980), and unsaturated hydraulic conductivity (Mualem, 1976) as a function of water content. The water retention parameter m was calculated as $1 - (1/n)$ according to van Genuchten (1980). The saturated hydraulic conductivity ranged from over 3 m/day to as little as 0.1 m/day (Table 2). For the uniform case, discussed later, the saturated hydraulic conductivity was set at 0.3 m/day.

The initial model saturation was calculated assuming matric potential in equilibrium with the water table. To account for the existence of naturally occurring nitrate and its entrainment by septic leachate, an initial nitrogen profile also was defined in the model. On the basis of water-extraction data from JTUZ-1, the initial nitrogen profile within the model simulation was approximately 25 mg/kg as N in the top 2 m of the soil, approximately 50 mg/kg as N between 2 and 20 m depth, and approximately 13 mg/kg as N between 20 m and the water table (approximately 165 m). Water within the saturated zone was defined as having an initial concentration of 2 mg/L nitrate as N.

A series of model runs were done to evaluate the effect of (1) housing density and (2) sloping layers within the unsaturated zone on water flow and transport of nitrate. The model was run using 0°, 2.5°, and 5° slopes of all unsaturated zone layers or set to uniform properties (saturated hydraulic conductivity 0.3 m/day). This resulted in six scenarios, 3 slopes for layered or uniform properties. Slope was simulated by changing the gravity vector in the model; the orientation of the finite-difference grid relative to the gravity vector was not changed. The uniform property, sloped simulations evaluate the effect of numerical dispersion within the model created using this approach. Housing density for each of the six layered scenarios within the model domain was set as one house with a septic tank and leach field per 0.1 ha lots for 1, 4, 16, 32, or 64 lots. A specified flux of 830 L/d was used to simulate discharge of septic tank effluent. Leachate from the septic system was simulated as 40 mg/l as N. The time period for each simulation was 100 years.

5.3. Model results

In the simplest case, with one house and one septic system on a single 0.1 ha parcel in the center of the model domain, septic leachate did not reach the water table during the 100-year simulation time period for all simulations (Table 3). With four houses and four septic systems on four 0.1 ha parcels centered in the model domain, the simulated leachate reached the water table within

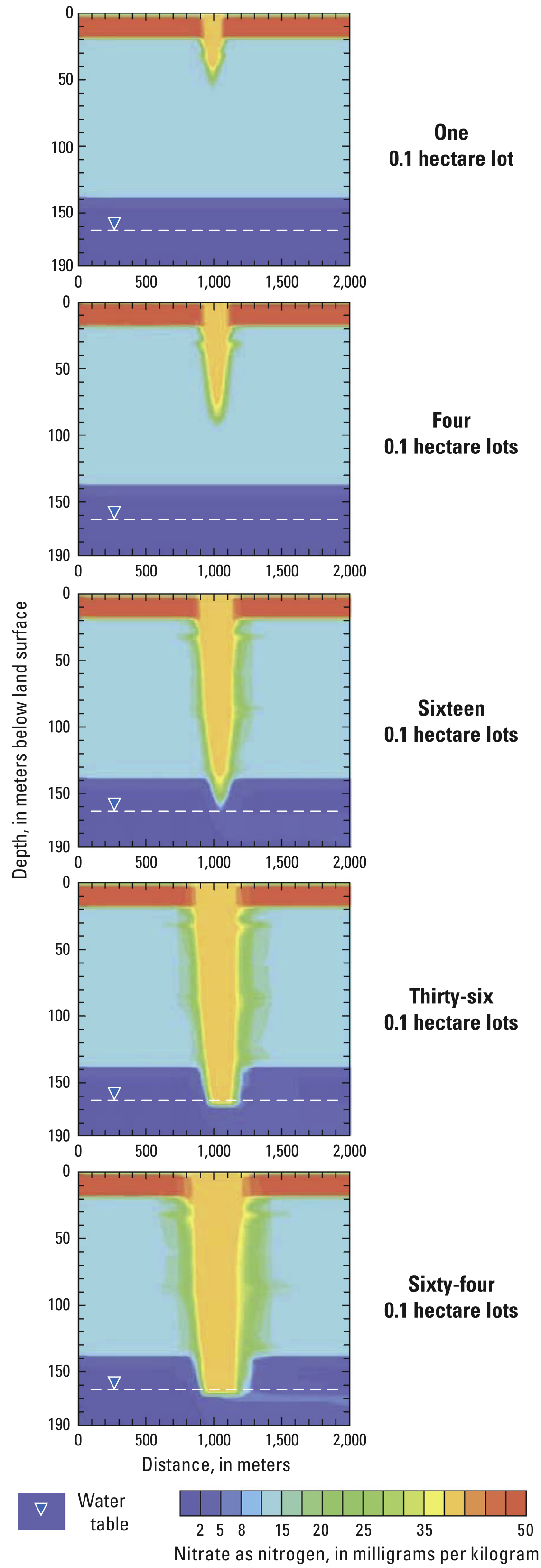

Fig. 14. Unsaturated-zone model simulation results showing nitrate concentrations within the unsaturated zone for different housing densities after 100 years for model layers sloping at 2.5°, Warren Groundwater Subbasin, western Mojave Desert, southern California.

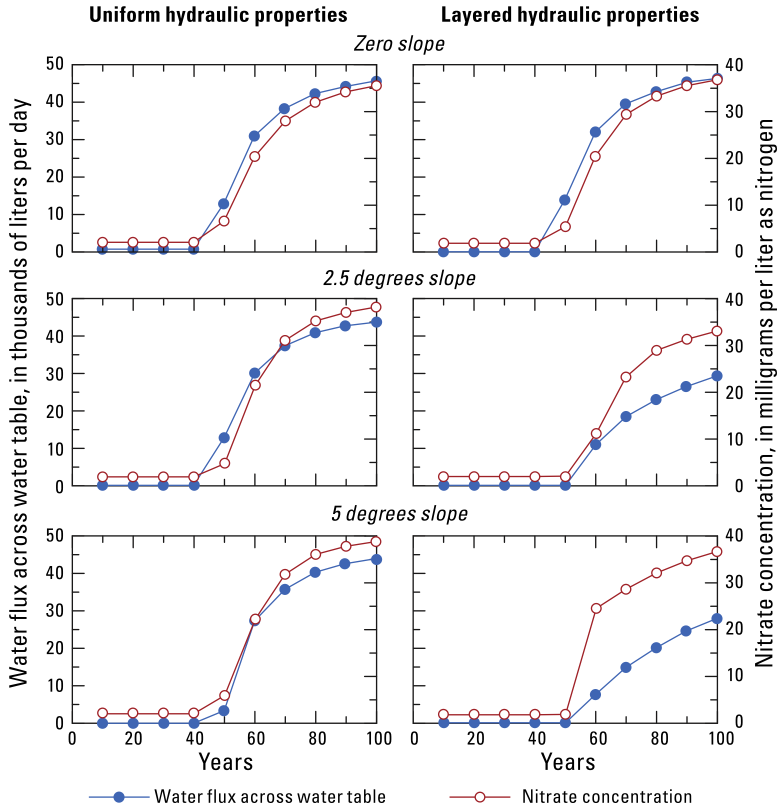

Fig. 15. Model simulation results showing water flux across water table and corresponding nitrate concentration for all model configurations for the maximum housing density simulated, 64 0.1 hectare parcels, Warren Groundwater Subbasin, western Mojave Desert, southern California.

85 years for the uniform hydraulic property simulations (not shown in Fig. 14) but did not reach the water table for any of the layered simulations (slope of 2.5° shown for Fig. 14). For the 16 septic system simulations, layering of hydraulic properties and increasing slope delayed the arrival of septic leachate at the water table compared to the uniform simulation results (Table 3). The highest density simulated was 64 houses with 64 septic systems on 0.1 ha parcels. For these simulations, septic leachate reached the water table in 45 years independent of layering and slope. This simulation represents a 6.4 ha development centered in a 400 ha open space. By the time the leachate reached the water table it extended out into the unsaturated zone approximately 60 m beyond the edge of the housing development. If the model had layered properties, the first arrival of water at the water table was delayed for the 4, 16, and 32 quarter-acre lots in comparison to the model with uniform properties. The increase in slope also delayed the arrival for layered model results for the 16 and 32 quarter-acre lot simulations (Table 3).

The 16 septic-system simulations were the first to result in significant flux to the water table, but only after 50 years of simulation (Table 3). By the end of the 100-year simulation these simulation resulted in flux rates of 8700 liters per day (L/d) for the uniform case and significantly less for the layered case with sloping layers. The nitrate concentration at the water table exceeded 30 mg/L as N in the uniform simulation but was only 4 mg/L as N for the non-sloping layered simulation. The sloping layered cases slowed the flow toward the water table by increasing lateral flow. However, increased lateral flow in the near surface facilitates more contact with the higher concentration nitrates in the upper 20 m of the unsaturated zone and ultimately results in a higher concentration of nitrate at the water table, although not all that nitrate would be from septic sources. For example, in the 64 quarter-lot simulation, even though the flow was less for the higher slope scenario (30,300 L/d versus 28,000 L/d), the nitrate concentration at the water table was greater (Table 3).

Water flux across the water table and the corresponding nitrate concentration for all model configurations for 64 septic systems are shown in Fig. 15. With no slope and uniform hydraulic properties, water and elevated nitrate concentrations reach the water table at nearly the same time. Small differences in water flux and nitrate concentrations in the uniformed hydraulic property simulations at 0°, 2.5°, and 5° slope are model artifacts resulting from changes in the gravity vector within the finite-difference grid used to simulate slope (Fig. 15). These simulation results are shown for comparison with the corresponding layered case. It takes longer for water to reach the water table as slope increases for the layered simulations. By the end of the 100-year simulation, water flux is less than the application rate for the 2.5° and 5° sloping scenarios, indicating the sloping layers impede the downward movement of water, and there is storage of water and nitrate within the unsaturated zone.

Model results suggest that greater housing densities in unsewered development over sloping alluvial fan deposits more than 150 m thick may have less impact on groundwater quality over management timeframes as long as 100 years, than similar housing densities over flat-lying unlayered alluvial deposits. However, over sufficiently long-timeframes in arid areas having thick unsaturated zones, input from septic discharges will ultimately equal water and nitrate fluxes reaching the water table.

5.4. Model limitations

The model is intended to be a conceptual simulation of how selected processes, such as housing density (quantity and spatial distribution of septic discharge), aquifer layering, and the slope of alluvial deposits, combine to influence the movement of water and nitrate associated with septic effluent through the layered unsaturated zone underlying unsewered residential development in the study area. The model results are not intended to be a simulation of septic effluent movement at any given location. Other factors (such as unsaturated-zone thickness and hydraulic properties, initial nitrogen concentrations within the unsaturated zone, and in some areas the potential for denitrification) also may influence the rate of water movement and nitrate transport associated with residential septic discharges through the unsaturated zone at a given location.

6. Summary and conclusions

Treatment and disposal of human waste through septic systems is a common practice in rural areas and some urban areas in United States and elsewhere in the world. In arid areas, recharge and dilution of septic waste from precipitation is minimal. The purpose of this study was to assess nitrate storage, potential for denitrification, and mobilization of nitrate from thick unsaturated zones underlying undeveloped, and unsewered residential and commercial land uses in an area of rising water levels resulting from managed groundwater recharge.

Nitrate storage in unsaturated zones greater than 100 m thick at two undeveloped sites, YVUZ-1 and YVUZ-5 in the western Mojave Desert, ranged from 420 to 570 kg/ha as N, and were similar to values expected for nitrate within thick undeveloped unsaturated zones elsewhere in the Mojave Desert (Izbicki et al., 2000a; Clark et al., 2009). A third undeveloped site, JTUZ-4, had nitrate storage within unsaturated alluvium of 6,600 kg/ha as N. This value is within the range of nitrate storage in unsaturated alluvium at unsewered residential sites JTUZ-1 and YVUZ-2 of 6,100 and 9,200 kg/ha as N and is unusual compared to other sites sampled as part of this study and elsewhere in the western Mojave Desert (Izbicki et al., 2000a; Clark et al., 2009). The origin of the nitrate within the unsaturated zone at JTUZ-4 is unclear, but $\delta^{18}O–NO_3$ data suggest the nitrate may be related to infiltration of surface flows in the nearby wash. Nitrate storage within thinner alluvium (less than 16 m thick) beneath sites irrigated with dairy wastewater was as great as 11,600 mg/kg as N. Data from the dairy sites were included in this study to provide an end member where more extensive nitrate reduction and denitrification occurred.

Infiltration of local groundwater from ponds at the YVUZ-5 site mobilized naturally-occurring nitrate from the unsaturated zone. This resulted in nitrate concentrations as high as 24 mg/L as N in the unsaturated zone and increased nitrate concentrations at the water-table well. Similar increases in nitrate may occur at the JTUZ-4 site as a result of infiltration from ponds proposed at this site. Although the mass of nitrate in the unsaturated zone at JTUZ-4 is almost an order of magnitude greater than the mass at YVUZ-5, actual concentrations at the water table as a result of proposed recharge will depend on the initial rate and volume of water infiltrated and will be limited to the nitrate in the unsaturated zone (largely within the upper 15 m) beneath the pond. Results from studies elsewhere in the Mojave Desert have demonstrated that increases in nitrate and other soluble salts mobilized as a result of infiltration from ponds are short in duration as nitrate and soluble salts are washed from the unsaturated zone (Izbicki et al., 2008).

Of greater concern than direct mobilization of nitrate from the unsaturated zone by infiltrating water is mobilization of nitrate beneath unsewered land use as the water table rises as a result of recharge. Nitrate concentrations at the water table underlying the unsewered land uses increased from 4.4 to 58 mg/L as N as the water table rose as a result of managed aquifer recharge. Because nitrate may be mobilized from large areas as the water table rises, this process may mobilize more nitrate than infiltration from ponds. Knowledge of the distribution of nitrate from septic discharges with depth in the unsaturated zone, and careful management of groundwater recharge to ensure the water table does not rise into parts of the unsaturated zone containing nitrate from septic discharges would ensure nitrate concentrations in groundwater do not increase as the water table rises in response to groundwater recharge.

Nitrate reducing and denitrifying bacteria are abundant even within alluvium beneath undeveloped land uses. On the basis of soil–gas, $\delta^{15}N–NO_3$, and $\delta^{18}O–NO_3$ data, nitrate removal through denitrification is typically less than 5% of the nitrate from septic sources. However, measurable denitrification within microsites and perched layers in the unsaturated zone and removal of as much as 40% of nitrate from septic sources can occur. Nitrate removal was as great as 30% in the unsaturated zone and near the top of the water table underlying dairy wastewater irrigated sites, possibly because of the greater organic load in dairy wastewater compared to septic sources.

Attenuation of nitrate from septic discharges reaching the water table through thick unsaturated zones in arid areas is largely through storage within the unsaturated zone. Numerical modeling done as part of this study indicates that storage within a 136 m thick unsaturated zone having uniform hydraulic properties can delay the arrival of septic discharges to the water table by more than 45 years depending upon the density of development and the volume of discharge. Sloping layers within the unsaturated zone that allow lateral movement of water and septic discharges within thick unsaturated zones can further delay the arrival of septic discharges for as much as 100 years depending upon specific conditions. Nitrate storage within the unsaturated zone may allow for management opportunities in areas underlain by thick unsaturated zones. For example, managing housing density can delay the arrival of septic discharges and increasing nitrate concentrations at the water table allowing time for development of a tax base to support infrastructure necessary address future water-quality issues. However because both microbiological processes that remove nitrate and dilution from precipitation are limited in thick unsaturated zones in arid areas, even the most careful management strategies and controls on housing density ultimately can only delay groundwater quality issues associated with septic discharges. In these areas changes in water management practices associated with managed groundwater recharge that rapidly raise the water table may increase nitrate concentrations sooner than expected. Conversely, model results suggest that in areas of existing unsewered residential development groundwater-quality issues associated with septic discharges may get progressively worse over long-time frames as septic discharges move through the unsaturated zone and nitrate contributions to the water table continue to increase decades after the initial development.

Acknowledgements

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2015.02.005.

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From: Cass, Jehiel@Waterboards
Sent: 2/10/2017 3:40:03 PM
To: Phillippe, Jason (Jason.Phillippe@dph.sbcounty.gov), Joshua Dugas (Joshua.Dugas@dph.sbcounty.gov)
cc: Coony, Mike@Waterboards, Kemper, Lauri@Waterboards, Copeland, Patrice@Waterboards
Subject: RE: LAMP Meeting Follow-up

Joshua and Jason: In further discussion with our Executive Officer on the San Bernardino County LAMP, the county's justifications for the proposed density of ½ acre per single family home would be strengthened if information such as the following is provided.

- Identification of areas where small lots won't make much impact versus areas where development is slated to be on sewers.

- Discussion of areas where septic systems are likely to occur in the future.

- Analysis of how many septic systems can be expected and why they may or may not cause harm in future.

We are trying to arrange a meeting between local agencies including San Bernardino County, City of Barstow, and Victor Valley cities and invite the USGS to discuss the pros and cons of using a vadose model for future analysis. We are thinking of a March 2017 time frame.

Regards – Jay

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----------------- Reply separator --------------------

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To: Phillippe, Jason (Jason.Phillippe@dph.sbcounty.gov), Joshua Dugas (Joshua.Dugas@dph.sbcounty.gov)
cc: Coony, Mike@Waterboards, Kemper, Lauri@Waterboards, Copeland, Patrice@Waterboards
Subject: RE: LAMP Meeting Follow-up