

# GROUND-WATER QUALITY IMPACTS FROM ON-SITE SEPTIC SYSTEMS

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## Abstract

Septic systems can contaminate ground water with dissolved solids, nitrate, anoxic constituents (manganese, iron and hydrogen sulfide), organic compounds, and microorganisms. In New Mexico, on-site septic systems have contaminated more acre-feet of ground water, and more public and private water supply wells, than all other sources combined. Contaminant concentrations can exceed allowable standards to protect human health and the aesthetic qualities of domestic water. Lot size is a critical factor in determining the amount of natural attenuation that occurs between the location where septic effluents enter the aquifer, and the nearest down-gradient point of ground-water withdrawal and, thus, the potential for water-well contamination.

There is a widespread misperception that nitrate is a universal indicator of ground-water contamination by sewage. Septic systems have caused regional nitrate contamination in many areas, but only in oxic aquifers. In anoxic conditions, the ammonia in sewage may not undergo nitrification, and ground-water nitrate contamination typically does not occur. Anoxic aquifers, however, are also vulnerable to chemical contamination from sewage. Microbial biodegradation of the organic matter added by septic effluent can change the chemistry of the aquifer, and cause increased amounts of manganese and iron to dissolve into the ground water from soil and rock.

Chloride and stable isotopes are used to geochemically fingerprint the impacts of septic systems versus other sources of ground-water contamination. Chloride is a useful indicator parameter for septic-system impacts because it is a non-reactive solute that occurs in all sewage. Chloride-nitrate ratios can be used to differentiate between potential nitrate sources. Stable isotopes also can be useful diagnostic parameters for source identification. Ground-water nitrate originating from septic systems and primary sewage-treatment plants is enriched with  $^{15}\text{N}$  due to biological fractionation. Biological de-nitrification in tertiary sewage treatment facilities further enriches nitrate with  $^{15}\text{N}$ , and this is reflected in plumes from those sites. Nitrate originating from fertilizers, explosives, and nitric acid has proportionately less  $^{15}\text{N}$  in source-area ground water, than does nitrate from sewage contamination. Caution must be exercised when interpreting nitrogen isotope data. If ground-water de-nitrification occurs during migration away from any nitrate source area,  $^{15}\text{N}$  enrichment will occur. Septic effluent discharged below the ground surface is not subject to the evaporative enrichment of  $^{18}\text{O}$  that can occur in wastewater ponds, and this is reflected in the isotopic composition of ground water impacted by these sources.

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## Introduction

Conventional septic tanks and drainfields are a suitable means of on-site wastewater treatment and dispersal when lot size and subsurface conditions provide adequate natural attenuation. Septic effluent also can be lost to evapotranspiration or prevented by geologic barriers from seeping into some aquifers. The amount of septic effluent credited as “return flow” to ground water is of interest for water rights purposes in New Mexico. Widespread ground-water contamination, however, has occurred in many rural areas utilizing on-site wells and septic systems (N.M. WQCC, 2002a). Effluent discharged to the subsurface by drainfields often percolates into the same aquifer tapped by wells for domestic supply. In New Mexico, on-site septic systems have contaminated more acre-feet of ground water, and more public and private water supply wells, than all other sources combined (Figure 1).

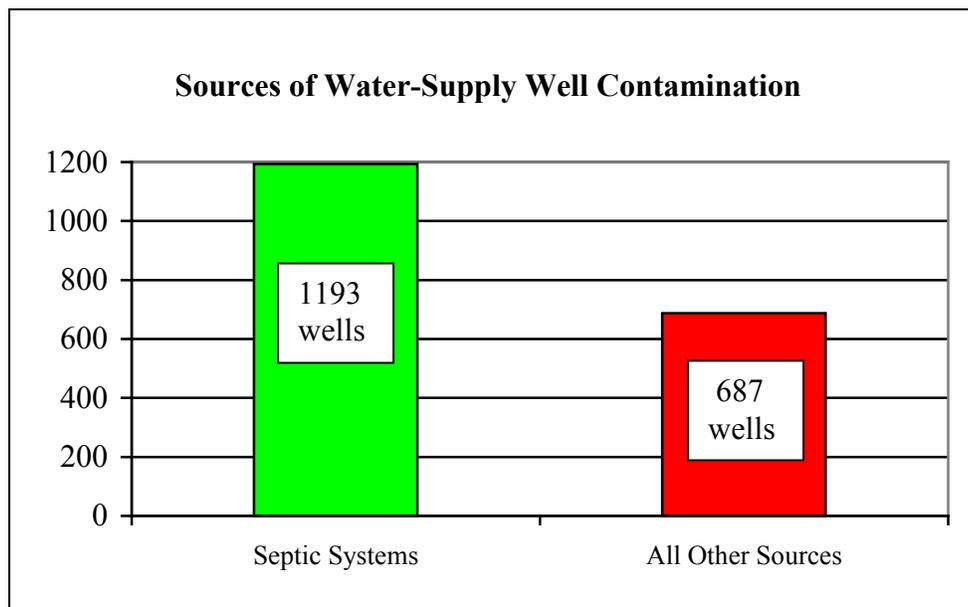


Fig. 1. New Mexico Water-Supply Wells Contaminated by On-site Septic Systems versus All Other Sources, Combined. (Modified from WQCC, 2002a)

Lot size is a critical factor in determining the amount of natural attenuation that occurs between the location where septic effluents enter the aquifer, and the nearest down-gradient point of ground-water withdrawal. A number of field studies and modeling simulations have addressed the effect of lot size on ground-water quality (Woodward et al., 1961; Konikow and Bredehoeft, 1978; Ford et al., 1980; Perkins, 1984; Yates, 1985; Earp and Koschal, 1986; McQuillan et al., 1989; Lowe et al., 2000). In New Mexico, residential developments with average lot sizes up to 0.84 acre (including roadways) have caused ground-water contamination in excess of allowable standards.

Domestic water use adds dissolved minerals and organic matter (typically measured as biochemical oxygen demand, BOD) to sewage (Table 1). Sewage also contains microorganisms, and can contain heavy metals and organic chemicals including solvents, petroleum hydrocarbons, caffeine, and pharmaceuticals. These added materials have different subsurface migration and fate characteristics, and can impact ground water either by direct discharge or indirectly by facilitating chemical alteration

of minerals in the vadose zone (the unsaturated zone overlying ground water) and in the aquifer.

Table 1. Mass loading from water use. Range A: domestic water use, excluding commercial and industrial additions and water softeners (Tchobanoglus and Burton, 1991). Range B and average B: increases from tap water to secondary effluent in 22 U.S. cities, including commercial and industrial additions (Snoeyink and Jenkins, 1980). Range C: residential water use (U.S. EPA, 2004).

| <b>Parameter (mg/L)</b>                      | <b>Range A</b> | <b>Range B</b> | <b>Average B</b> | <b>Range C</b>                      |
|--|----------------|----------------|------------------|-------------------------------------|
| Total Dissolved Solids (TDS)                 | 150 to 380     | 128 to 541     | 320              |                                     |
| pH (units)                                   |                | -1.7 to 0      | -0.6             |                                     |
| Anions:                                      |                |                |                  |                                     |
| Chloride (Cl <sup>-</sup> )                  | 20 to 50       | 6 to 200       | 74               |                                     |
| Sulfate (SO <sub>4</sub> <sup>2-</sup> )     | 15 to 30       | 12 to 57       | 28               |                                     |
| Bicarbonate (HCO <sub>3</sub> <sup>-</sup> ) | 50 to 100      | -44 to 265     | 100              |                                     |
| Carbonate (CO <sub>3</sub> <sup>2-</sup> )   | 0 to 10        |                |                  |                                     |
| Fluoride (F <sup>-</sup> )                   | 0.2 to 0.4     |                |                  |                                     |
| Cations:                                     |                |                |                  |                                     |
| Calcium (Ca <sup>2+</sup> )                  | 6 to 16        | 1 to 50        | 18               |                                     |
| Magnesium (Mg <sup>2+</sup> )                | 4 to 10        | Trace to 15    | 6                |                                     |
| Sodium (Na <sup>+</sup> )                    | 40 to 70       | 8 to 101       | 66               |                                     |
| Potassium (K <sup>+</sup> )                  | 7 to 15        | 7 to 15        | 10               |                                     |
| Nitrogen:                                    |                |                |                  |                                     |
| Nitrate (NO <sub>3</sub> <sup>-</sup> )      | 20 to 40       | 0.1 to 2       | 1                |                                     |
| Nitrite (NO <sub>2</sub> <sup>-</sup> )      |                | -5 to 26       | 10               |                                     |
| Ammonium (NH <sub>4</sub> <sup>+</sup> )     |                | 0 to 36        | 15               | 4 to 13                             |
| Nitrogen, total                              |                |                |                  | 26 to 75                            |
| Phosphorus:                                  |                |                |                  |                                     |
| Phosphate (PO <sub>4</sub> <sup>3-</sup> )   | 5 to 15        | 8 to 40        | 24               |                                     |
| Phosphorus, total                            |                |                |                  | 6 to 12                             |
| Other Inorganic:                             |                |                |                  |                                     |
| Aluminum (Al)                                | 0.1 to 0.2     |                |                  |                                     |
| Boron (B)                                    | 0.1 to 0.4     |                |                  |                                     |
| Manganese (Mn)                               | 0.2 to 0.4     |                |                  |                                     |
| Silica (SiO <sub>2</sub> )                   | 2 to 10        | 9 to 22        | 15               |                                     |
| Organic:                                     |                |                |                  |                                     |
| BOD (5 day)                                  |                |                |                  | 155 to 286                          |
| Fats, Oils, and Grease                       |                |                |                  | 70 to 105                           |
| Volatile Organic Compounds                   |                |                |                  | 0.1 to 0.3                          |
| Surfactants                                  |                |                |                  | 9 to 18                             |
| Total Coliforms                              |                |                |                  | 10 <sup>8</sup> to 10 <sup>10</sup> |
| Fecal Coliforms                              |                |                |                  | 10 <sup>6</sup> to 10 <sup>8</sup>  |

## Contamination Geochemistry

The types of ground-water contamination caused by on-site septic systems are summarized in Table 2. Of the dissolved solids added by domestic use (Table 1), chloride is a good indicator parameter of sewage impacts because it is not subject to adsorption, ion exchange, or oxidation-reduction “redox” reactions. The correlation between elevated chloride and nitrate in an area of known septic-system contamination is shown in Figure 2. Chloride increases linearly from a background of about 20 mg/L with increasing nitrate. Waste from the regeneration of water softeners, if discharged to septic systems, can add significant amounts of chloride and sodium or potassium.

Table 2. Ground-water contamination from septic systems. Standards: N.M. WQCC (2002b).

| Contaminant   | Oxic Conditions | Anoxic Conditions | Ground-Water Standard (mg/L)    |
|---|-----------------|-------------------|---------------------------------|
| TDS (chloride, sodium, etc.)                                | X               | X                 | TDS 1000<br>Cl <sup>-</sup> 250 |
| Nitrate   | X               |                   | 10 as N                         |
| Anoxic Constituents (manganese, iron, and hydrogen sulfide) |                 | X                 | Mn 0.2<br>Fe 1.0                |
| Organic Compounds (solvents, pharmaceuticals, etc.)         | X               | X                 | various                         |
| Microbes  | X               | X                 | No standards                    |

Redox reactions involve the transfer of electrons, and can strongly influence the geochemistry of septic effluents and ground water. In oxic conditions, where dissolved oxygen is present, the ammonia in sewage can be oxidized to nitrate (nitrification), which can contaminate ground water. Nitrification often occurs in the vadose zone before effluent percolates to ground water. Septic systems have polluted ground water in numerous areas of New Mexico with nitrate at concentrations exceeding the allowable human-health standard of 10 mg/L as N (Table 2).

Anoxic ground water contains no dissolved oxygen and may not support ammonia nitrification. Ammonia, as the ammonium ion however, can be removed by cation exchange. Anoxic conditions can occur naturally, such as in soils that contain decaying plant material or in rocks containing organic carbon. Indigenous microbes use this organic matter for energy production and cell growth. The organic matter serves as an electron donor and is oxidized. In this process, another material must serve as an electron acceptor, and undergo reduction. Ground-water microbes preferentially utilize (respire) electron acceptors that yield the highest energy (Figure 3). Electron acceptors that yield greater energy are consumed before constituents that yield lower energy. De-nitrification, the conversion of nitrate to nitrogen gas (N<sub>2</sub>), only occurs in anoxic conditions after dissolved oxygen has been consumed by aerobic respiration (Figure 3). This fact has long been known to wastewater professionals who use de-nitrification for tertiary treatment. If nitrate is discharged into anoxic ground water, or if oxic ground water containing nitrate either migrates into anoxic conditions or is made anoxic by anthropogenic discharges, de-nitrification can occur. Once dissolved oxygen and nitrate have been consumed, microbes will utilize manganese oxides in the soil or rock as the electron acceptor (Figure 3). Manganese contained in the insoluble oxide mineral is chemically reduced to Mn<sup>2+</sup> and can then

dissolve into ground water as a free ion. Iron oxide minerals also can be respired in this manner (Figure 3). Sulfate, which is a common natural ground-water anion and is added to sewage by domestic use (Table 1), can be reduced to hydrogen sulfide. Sulfate reduction yields less energy to the microbes than manganese and iron reduction (Figure 3). Methanogenesis, the production of methane, a reaction long known to petroleum geologists, yields the least energy of these reactions.

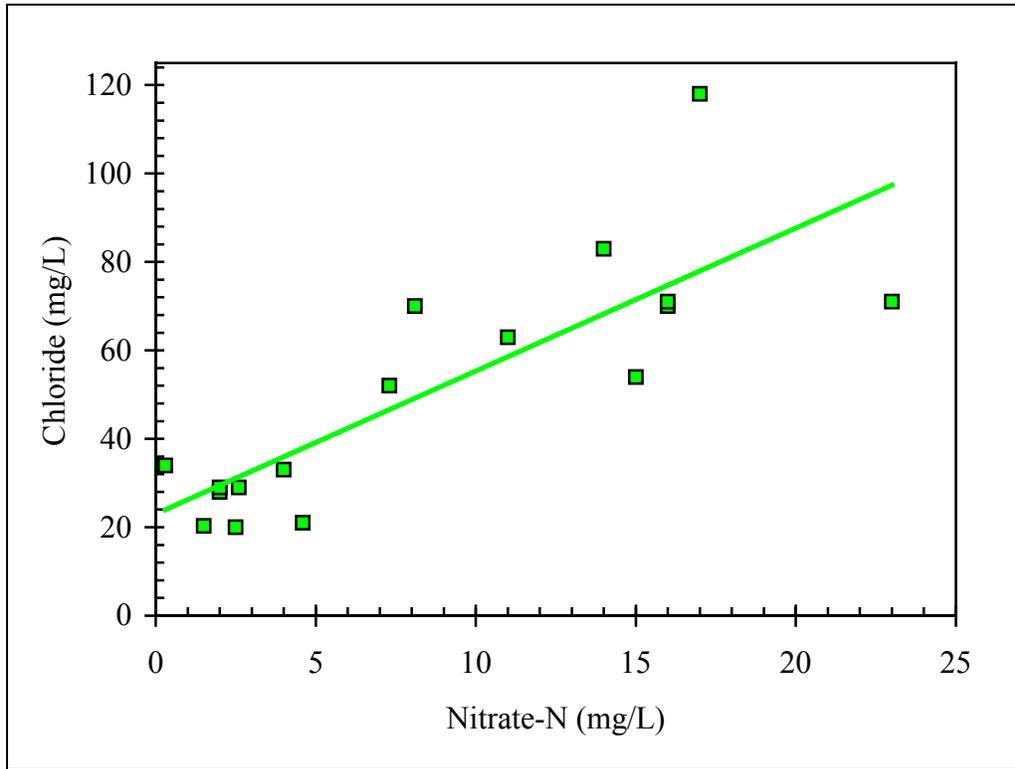


Fig. 2. Chloride and Nitrate in Ground Water in an Area Impacted by Septic Systems. All data are from a residential area, with oxic ground-water conditions, served by on-site domestic wells and septic systems, located in the Albuquerque West Mesa (McQuillan et al., 1989).

| <b>Reduction Reactions</b><br>decreasing energy yield |  |
|---|--|
| • Aerobic respiration                                 |  |
| • Denitrification                                     |  |
| • Manganese reduction                                 |  |
| • Iron reduction                                      |  |
| • Sulfate reduction                                   |  |
| • Methanogenesis                                      |  |

Fig. 3. Decreasing Energy Yield of Electron-Acceptor Reduction Reactions Used by Ground Water Bacteria for Respiration.

Ground-water microbes also will oxidize anthropogenic sources of organic matter (sewage discharges,

petroleum spills, etc.) as a carbon-energy source. These discharges can make oxic ground water become anoxic, a phenomenon observed at some industrial pollution sites. This alteration to anoxic conditions, however, can be temporary with oxic conditions returning after the carbon source has been consumed. One area of the Pojoaque Valley in N.M. currently appears to be undergoing the development, or worsening, of anoxic conditions. It is not clear whether this is being caused by the on-site septic systems in the area, or by the decreased recharge of oxygenated meteoric water related to the on-going drought. Discharges of organic matter to existing anoxic ground water also can cause microbes to consume greater amounts of electron acceptors, thereby increasing concentrations of manganese, iron, and hydrogen sulfide. In the Albuquerque South Valley, the highest concentrations of ground-water manganese (greater than 1 mg/L) are associated with areas having the highest densities of on-site septic systems (Gallaher et al., 1987), and there appears to be a similar association with ground-water iron (Anderholm, 1987). Hydrogen sulfide occurs in many wells in this area, and some are methanogenic. Manganese, iron, and hydrogen sulfide can seriously impair the aesthetic qualities of domestic water by imparting unpleasant tastes and odors, and by staining laundry and plumbing fixtures. High levels of manganese in drinking water also may cause neurotoxicity (ATSDR, 2000). A lifetime health advisory for manganese in drinking water has been set at 0.3 mg/L (U.S. EPA, 2004).

A variety of organic compounds including solvents, petroleum hydrocarbons, and pharmaceuticals can be discharged in household sewage. Dichlorobenzene, a common constituent of deodorizer toilet blocks, has contaminated ground water in New Mexico as a result of on-site septic system discharges. In a preliminary survey, pharmaceuticals were not detected in ground water samples from eight nitrate-contamination sites in New Mexico, seven of which were caused by sewage (McQuillan et al., 2001).

Coliform bacteria, including fecals, have been detected in some private domestic wells in areas contaminated by on-site septic systems. These occurrences, however, appear to be localized and do not indicate regional microbial contamination, unlike septic-system plumes of nitrate and anoxic conditions.

### **Geochemical Fingerprinting of Ground-Water Nitrate Contamination**

Sources of ground-water nitrate contamination include septic systems, sewage treatment plants, dairies and other animal wastes, commercial fertilizers, explosives waste, nitric acid waste, mining/milling wastes, and natural geologic sources (marine deposits and evaporation of atmospheric recharge along ephemeral watercourses). The source of nitrate contamination is not always evident, and sometimes there are multiple sources. Chloride and stable isotopes of hydrogen, oxygen, and nitrogen can be useful diagnostic parameters for source identification.

Ground-water nitrate and chloride concentrations from three different types of sources are compared in Figure 4. Dairy plumes contain the highest levels of nitrate and chloride. Ground water plumes caused by septic systems contain lower concentrations of both nitrate and chloride. Ground water contaminated by evaporative concentration of rainwater beneath ephemeral streams (McQuillan and Space, 1995), contains relatively low chloride concentrations, consistent with local meteoric (atmospheric) water. Rainwater collected in the Jemez Mountains of New Mexico contains a 2.22 ratio of nitrate-N to chloride (NADP, 1982-2001). This ratio was used to plot the meteoric concentration line (Figure 4), which correlates with nitrate and chloride ratios in evaporation plumes.

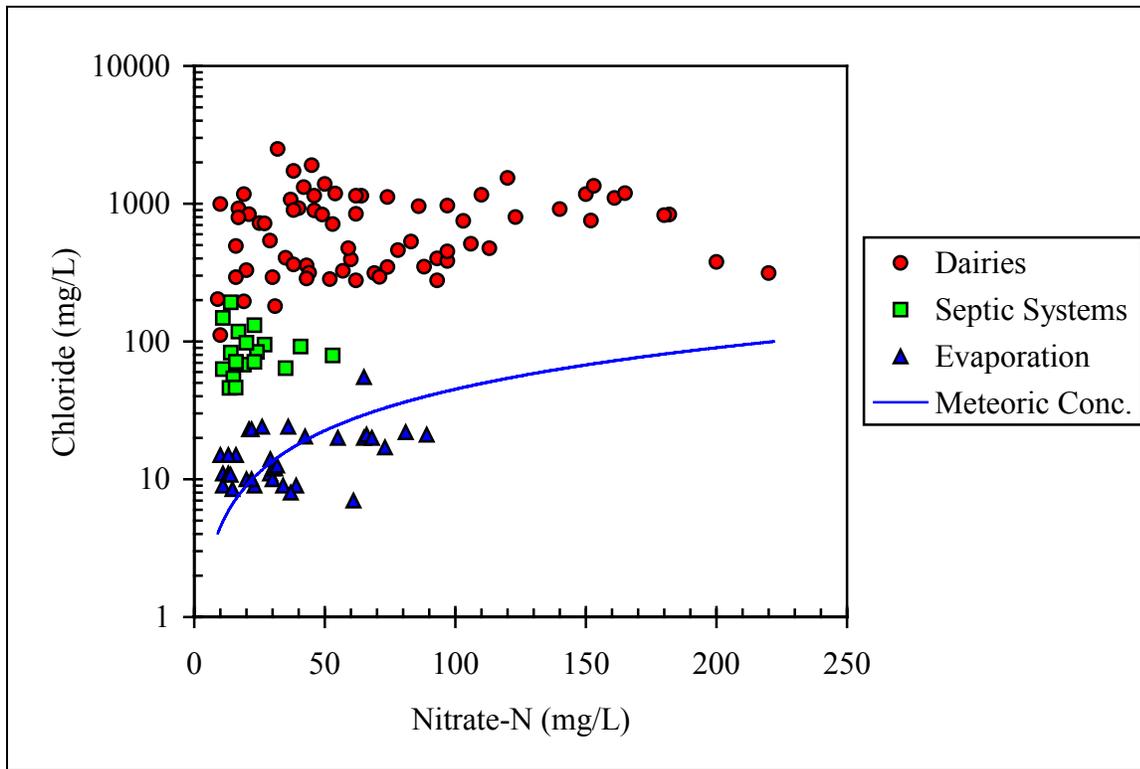


Fig. 4. Chloride and Nitrate in Contaminated Ground Water. All data are from the Middle Rio Grande Valley, N.M. Background chloride at each site is less than 20 mg/L. (N.M. Environment Department monitoring data and permit files)

Stable (non-radioactive) isotopes of the same element differ by the number of neutrons in the atomic nucleus. A variety of physical and biological processes can affect the relative concentrations of light and heavy isotopes of the same element. This relative enrichment or depletion of one stable isotope over another is called isotopic fractionation. During evaporation, for example, the heavier  $^{18}\text{O}$  becomes enriched in the residual water as more of the lighter  $^{16}\text{O}$  enters the vapor phase. Thus, meteoric water, derived largely from the evaporation of ocean water, is enriched with  $^{16}\text{O}$  relative to ocean water. Biological organisms preferentially use  $^{14}\text{N}$ , rather than  $^{15}\text{N}$ , for respiration and assimilation because the chemical bonds of lighter isotopes are generally broken more easily than those of heavier isotopes (Bates and Spalding, 1998).  $^{14}\text{N}$  becomes concentrated in cell mass while  $^{15}\text{N}$  becomes concentrated in the residual nitrogen source and in human and animal wastes (Kreitler, 1975). In addition, a disproportionate amount of  $^{14}\text{N}$  as compared to  $^{15}\text{N}$  is released to the atmosphere during ammonia volatilization from human and animal waste, fostering enrichment of  $^{15}\text{N}$ . Thus, nitrate in ground water that has been denitrified by microbes, or originates from human and animal waste, is enriched with  $^{15}\text{N}$ . These isotope fractionations have long been studied to trace flow paths and mixing of water sources (Craig et al., 1963), and to identify sources of nitrate and ammonia in ground water (Fogg et al., 1998; Kreitler, 1975). Isotopic compositions are usually presented as delta values (eg.  $\delta^{15}\text{N}$ ), which express the ratio of the heavy to light isotopes (ie.,  $^2\text{H}/^1\text{H}$ ,  $^{15}\text{N}/^{14}\text{N}$ , and  $^{18}\text{O}/^{16}\text{O}$ ), relative to a universal standard.

Stable isotope and anion/cation analyses were performed on 189 samples collected at 61 sites of ground-water nitrate contamination in New Mexico. When possible, samples were collected from wells in the source area and along a flow path away from the source area. The results of this study have been submitted as a manuscript to the Ground Water Journal (McQuillan et al, in progress), and are summarized here. The study produced two findings significant to the issue of nitrate contamination from on-site septic systems:

1. The  $\delta^{15}\text{N}$  signature of ground-water nitrate originating from on-site septic systems is differentiated from that of most other sources; and
2. Ground water contaminated with nitrate from on-site septic systems is not enriched with  $^{18}\text{O}$  as is ground water contaminated by pond seepage that has been subject to evaporative fractionation.

Maximum nitrate-N concentrations and the range of  $\delta^{15}\text{N}$  values for ground waters in close proximity to identified  $\text{NO}_3$  sources are summarized in Table 3 and Figure 5. Septic systems and sewage plants providing only primary treatment are characterized by nitrate contamination with similar  $\delta^{15}\text{N}$  signatures, and similar maximum nitrate-N concentrations. Tertiary-treated sewage effluents contaminate ground water with lower  $\text{NO}_3\text{-N}$ , but with heavier  $\delta^{15}\text{N}$  values. Dairy-waste plumes can have very high nitrate-N levels, and are significantly enriched with  $^{15}\text{N}$ . Atmospheric nitrogen ( $\delta^{15}\text{N}=0$ ) is used to manufacture explosives and fertilizers. Ground waters contaminated by these sources, as well as by evaporation of meteoric water, have  $\delta^{15}\text{N}$  signatures just slightly more positive than the atmospheric standard of zero (Figure 5). It is important to note that the  $\delta^{15}\text{N}$  data presented here are for source-area ground waters. At some sites, de-nitrification occurred as ground water migrated away from the source, resulting in  $^{15}\text{N}$  enrichment.

Stable isotope data for the hydrogen ( $\delta^2\text{H}$ ) and oxygen ( $\delta^{18}\text{O}$ ) in nitrate-contaminated ground water are presented in Figure 6. Ground waters contaminated by on-site septic systems plot close to the local meteoric water line, while those contaminated by seepage from waste ponds (dairy, sewage, and uranium mill tailings) showed the impact of evaporation and were enriched in  $^{18}\text{O}$  (Figure 6).

## **Discussion and Conclusions**

There is a widespread misperception that nitrate is a universal indicator of ground-water contamination by sewage. In fact, some regulatory programs are based on nitrogen loading rates. Septic systems have caused regional nitrate contamination in many areas, but only in oxic aquifers. In areas with anoxic conditions, however, ammonia nitrification may not occur, and nitrate typically does not contaminate ground water regardless of how much septic tank effluent is discharged into the aquifer. Nitrate discharged into anoxic ground water, such as in effluent from secondary treatment systems, should undergo de-nitrification unless it is accompanied by enough dissolved oxygen to sustain oxic conditions.

Table 3. Nitrate and  $\delta^{15}\text{N}$  in source-area ground water.

| Nitrate Source        | Nitrate-N (mg/L) maximum | $\delta^{15}\text{N}$ (‰) range & mean | Number of Samples |
|-----------------------|--------------------------|--|-------------------|
| Septic systems        | 53                       | 7.6 to 12.1<br>10.4 mean               | 12                |
| Primary sewage plant  | 56                       | 7.2 to 12.1<br>9.4 mean                | 4                 |
| Tertiary sewage plant | 19                       | 13.9 to 34.7<br>19.1 mean              | 9                 |
| Dairy                 | 220                      | 9.6 to 26.8<br>13.7 mean               | 9                 |
| Chemical fertilizer   | 43                       | 1.8 to 4.1<br>2.6 mean                 | 4                 |
| Explosives            | 109                      | 1.0 to 4.1<br>3.1 mean                 | 5                 |
| Nitric acid           | 38                       | -37.9 to 3.4<br>-9.29 mean             | 23                |
| Uranium mill          | 130                      | 12.0 to 26.6<br>16.9 mean              | 3                 |
| Evaporation           | 66                       | 2.2 to 6.7<br>5.0 mean                 | 22                |
| Marine deposit        | 320                      | 17.7<br>17.7 mean                      | 1                 |

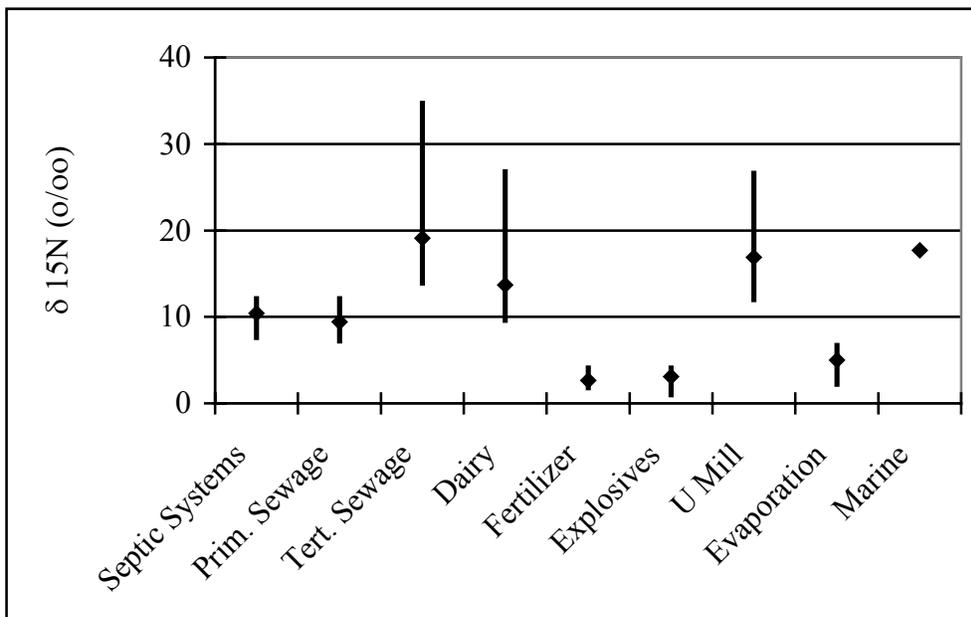


Fig. 5.  $\delta^{15}\text{N}$  in Source-Area Ground Water. Range and mean values.

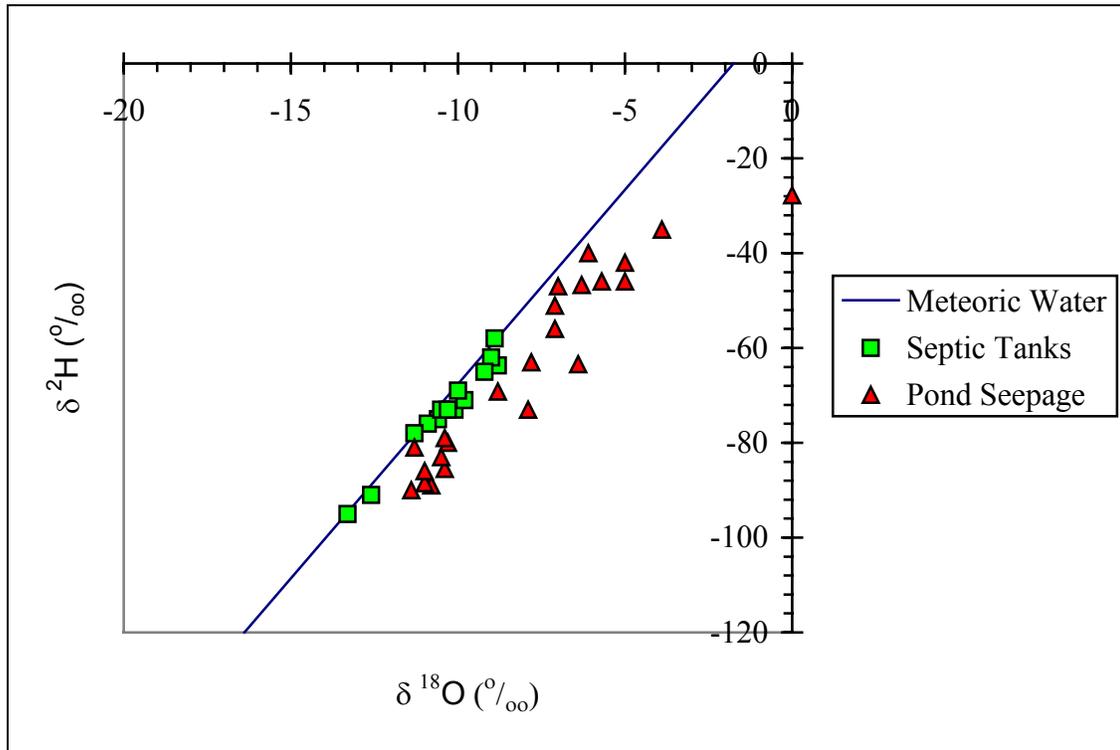


Fig. 6. Ground Waters Contaminated by Septic Tanks and Pond Seepage. Local meteoric water line for northern New Mexico,  $\delta^2\text{H} = 8.0 \delta^{18}\text{O} + 11.1$ , from Anderholm (1994).

Anoxic aquifers, however, are also vulnerable to chemical contamination from septic effluents. Microbial biodegradation of the organic matter (BOD) added by septic effluent can cause greater consumption of electron acceptors thereby increasing concentrations of manganese, for example. Anoxic ground water also can be contaminated by organic compounds and by pathogenic microorganisms.

Stable isotopes and chloride can be useful diagnostic parameters for source identification of ground-water nitrate. Chloride is a good indicator parameter for sewage contamination because it is present in all sewage, and is not subject to adsorption, ion exchange, or redox reactions. All ground water impacted by sewage in New Mexico contains elevated chloride. Septic systems typically add substantially less nitrate and chloride to ground water than do dairy wastes.

The  $\delta^{15}\text{N}$  signatures of ground-water contamination from septic tank effluents, and primary treatment sewage systems have similar ranges. Tertiary sewage treatment, which includes microbial denitrification and possibly ammonia volatilization, enriches  $\delta^{15}\text{N}$  beyond the level found in primary treated sewage, and this is reflected in ground-water nitrate plumes from tertiary sewage plants. Although unique  $\delta^{15}\text{N}$  have been reported for these and other potential nitrate sources, in source-area

ground water, these signatures can be obscured by de-nitrification during migration away from the source area.

Wastewater pond evaporation clearly causes  $^{18}\text{O}$  enrichment, and this is reflected in ground water contaminated by pond seepage. The lack of  $^{18}\text{O}$  enrichment observed in ground water contaminated by septic systems is consistent with effluent being discharged directly to the subsurface.

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