

**Sources of Nitrate Contamination in Ground Water of Pleasant Valley,
Power County, Idaho**

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Executive Summary

Major ion chemistry and stable isotope ratios, coupled within a hydrostratigraphic interpretational framework, were used to discriminate between shallow and deep ground water, to identify the presence of three different sources contributing to ground-water nitrate contamination, and to infer possible mechanisms by which the contamination has occurred.

Ground waters in the study area were classified into four types on the basis of their anion and stable isotope ($^{18}\text{O}/^{16}\text{O}$, $^2\text{H}/^1\text{H}$) ratios and their hydrogeologic context:

- (i) regional ground water not affected by canal seepage and/or evaporation (slightly to moderately contaminated by nitrate);
- (ii) shallow ground water affected by evaporation during sprinkler application and/or seepage of canal water (variably contaminated);
- (iii) shallow ground water locally enriched in chloride and sulfate, that is highly contaminated by nitrate; and
- (iv) canal water derived from the Snake River (uncontaminated).

Anion ratios, mixing relationships, and N-isotopes of dissolved nitrate-N were used to discriminate between three sources of nitrate contamination: (a) a ^{15}N -depleted inorganic fertilizer source seen only in type (ii) evaporation-affected shallow ground water; (b) a ^{15}N -enriched organic source associated with type (ii) water that is highly enriched in nitrate, chloride and sulfate derived from feedlot runoff; and (c) a septic source, characterized by Cl/NO_3 and Cl/SO_4 ratios virtually identical to domestic septic effluent-contaminated ground water that has been documented in the lower Portneuf River valley. Of these, fertilizer is the predominant source; even in wells having the most contamination from ^{15}N -enriched organic waste, fertilizer appears to comprise 40-80 percent of the total contaminant nitrogen load. Spring Hollow's nitrate appears to be solely of fertilizer origin, based on the following evidence:

- a) from its stratigraphic position relative to the aquifer, the spring likely reflects discharge from a shallow water table that is perched on a clay aquitard underlying Spring Hollow's watershed;
- b) Spring Hollow's water has undergone significant evaporation, raising its ^{18}O isotope content by 1 per mil and its ^2H content proportionately in a manner that only evaporation can;
- c) chloride is also more than four-fold enriched relative to the ground water that supplies the pivots, also indicating that Spring Hollow's water has been exposed to extensive evaporation.

Localized septic contamination is characterized by more variable anionic ratios and may reflect poor well construction and/or well siting. Regional ground water from the deep aquifer also has septic-like anion ratios but with more uniform Cl/NO_3 and Cl/SO_4 ratios. Although the septic source(s) of this contamination could be locally derived, they could be derived from distant septic inputs that are homogenized during regional-scale ground-water transport from upgradient source areas. Regardless of provenance, it is clear that septic effluent is impacting the deeper aquifer and a measurable cumulative impact on regional water quality in this aquifer.

1. Introduction

1.1. Background and Statement of the Problem

Nitrate is the most pervasive contaminant in Idaho ground water, affecting more than 35 percent of statewide monitoring wells (Neely, 2005). During informal surveys of local ground-water quality in the Pleasant Valley area of southeast Idaho, near American Falls, some of the highest nitrate levels in the state have been documented (Poulson, 2004; N. Poulson, 2007, written comm.). Two features are noteworthy: (i) the extremely high nitrate-N concentrations that characterize a natural seep at Spring Hollow (**Figure 1**), approaching 50 mg/l (**Figure 2**); and (ii) apparent vertical demarcation of nitrate levels, wherein shallow ground water bears the brunt of nitrate contamination and deep ground water seldom if ever displays elevated nitrate concentrations.

Of the potentially contaminating sources in the area the most likely ones, based on the types of local land uses, are fertilizer (non-point), septic and feedlot (point) sources. A fourth potential source, waste water derived from potato processing, is known to be a major nitrate source down-gradient of ConAgra's plant east of American Falls (Coffan, 2003) but is not thought to be a factor in the Pleasant Valley area. This study was undertaken to document and corroborate earlier findings of nitrate contamination in order to evaluate the state of ground-water quality up-gradient of the ConAgra site and to determine whether specific land uses in the Pleasant Valley area could be identified as potential sources of nitrate contamination.

1.2. Scope and Objectives

The objectives of the study were to:

- characterize ground-water quality upgradient of the ConAgra site
- interpret water-quality variations in a hydrostratigraphic context
- evaluate the influence of canal leakage on local ground-water quality
- identify the most likely nitrate sources and mode(s) of contamination
- develop testable hypotheses for Spring Hollow's chronically high nitrate levels

The study area delineated in **Figure 1** was a compromise designed to achieve the above objectives in light of limited hydrogeologic information (access to private wells, ability to measure static water levels) and the constraints imposed by financial and personnel resources that were available to the study. Mr. Neil Poulson of Poulson Associates, American Falls, was the subcontractor in charge of contacting well owners and identifying accessible wells, collecting water-level measurements and conducting the water sampling.

The excellent rapport that Mr. Poulson had with local landowners--and the fact that he is a landowner and farmer himself--allowed virtually complete access to all wells deemed worthy of investigation. Despite this, the study faced three principal limitations: very few shallow-deep well pairs were available to evaluate vertical hydrogeologic and water-quality variations; well logs were available for only about a third of the wells sampled and the effective sampling depth

of many wells was unknown; access to almost all wells was severely limited by wellhead construction/completion constraints that resulted in limited ability to purge, few reliable water-level measurements and, in the case of irrigation wells, the ability to sample only during the irrigation season.

2. Methods

2.1. Study Area and Sampling Sites

The study area is situated on loess-covered basalts of the eastern Snake River Plain aquifer. Topographic relief is fairly muted, with gentle hills and valleys developed around low-altitude shield volcanoes sloping eastward to a putative glacial lake shore and the American Falls Reservoir (**Figure 3**). The Aberdeen-Springfield canal system extends over the eastern portion of the study area, generally filling and draining in late April and late October, respectively. Regional ground-water flow is generally to the south-southwest, with local and seasonal perturbations introduced by the reservoir and reservoir dynamics and by local water table mounding induced by waste-water percolation ponds and the canal system (Coffan, 2003; Poulson, 2004). The topographically-defined watershed east of the Pleasant Valley's shield volcano defines the approximate area from which Spring Hollow derives meteoric water via direct infiltration of precipitation as well as of irrigation water, but it likely does not identify the source area of its ground water recharge which almost certainly crosses topographic divides in this low-relief terrain.

Figure 3 shows the locations of wells and natural seeps that were sampled during this study and **Figure 4**, the locations of available well logs for those wells that were sampled and wells that could be accessed for water-level measurements. **Appendix A** contains field notes describing the sampling sites and the details of sample collection.

2.2. Subsurface Stratigraphy

Subsurface stratigraphy of the eastern Snake River Plain has been shown to be systematically interpretable using lithologic descriptions derived from State of Idaho drillers' reports (Phillips and Welhan, 2006). Drillers' reports were downloaded from the Idaho Department of Water Resources on-line database (IDWR, 2007). Reported depths to lithologic contacts were converted to elevations using wellhead elevations interpolated from 10-meter digital elevation models (Inside Idaho, 2007). Lithologic cross-sections were constructed on the basis of these interpreted logs by correlating reported occurrences of sediment intercalated within the basalt, using the method of Phillips and Welhan (2006).

2.3. Water Level Measurements

Water levels were measured by the electrical (conductance) method. In some wells, the electric sonde could not be deployed and/or retrieved reliably because of the obstructions created by pump cables and riser pipe, so an ultrasonic time-of-travel sounding device was also used. Measurements made by the two methods agree to 0.14 meters on average. Data are summarized in **Table 1**.

2.4. Major and Minor Ions

Samples were collected in two synoptic campaigns, during October-November, 2006 and again in April, 2007 to characterize ground-water quality without the diluting influence of canal water infiltration. At selected sites, samples were also collected on an approximately monthly basis prior to and after the canals drained and filled, to determine the effect of seasonal dilution by canal water on shallow ground-water.

In all cases, well-water samples were collected from a spigot or outlet as near to the wellhead as was practical. In most cases, we had no control over sampling pump vs. pressure tank discharge or the length of time that the pump operated. Because of restrictions imposed by the well owner and/or the location of the sampling point, a number of wells could not be purged for more than 30-60 seconds. In one situation (site #18), where the three-volume purge time of wellhead plumbing exceeded 10 minutes, a set of samples collected at 0.5, 3, and 10 minutes after the start of flow indicated no detectable trends in major or minor ion concentrations (**Table 3**). Therefore, to maintain consistency of purge times between sites, a 30-second purge was used throughout. At Spring Hollow, the seep cannot be sampled directly because its discharge point is always below the level of the estuary that it supports; water samples were collected by submerging the collection container at the head of the estuary as near the submerged rock face as possible where active discharge was visible. Furthermore, a local return-flow canal discharges into the estuary where the seep's discharge occurs, making it impossible to collect spring samples that have not been diluted by canal water except when the canals have drained.

Samples were collected in 1-liter polyethylene bottles and kept chilled until day's end, at which time they were delivered to Magic Labs' Pocatello office and shipped to Twin Falls in coolers. Sampling information was entered on standard chain-of-custody forms together with the type of analyses desired. In all cases, samples arrived at the laboratory within 24 hours of collection and were analyzed well within the maximum holding times specified for the EPA analytical methods that were used (**Appendix A**). All samples were analyzed for major cations (Ca, Mg, Na, K) and anions ($\text{CO}_3 + \text{HCO}_3$, Cl, SO_4), as well as $\text{NO}_3\text{-N}$. Initially, Br analyses were requested as an independent tracer that might help discriminate between water sources, but when the detection level proved to be too high for the Br levels found in most samples, F analyses were substituted.

In all cases, reproducibility of major ion concentrations in replicate samples (**Tables 2**) was good to excellent. Root mean square charge-balance error was within 4 percent and average charge-balance error was 2 percent (**Table 3**).

2.5. Stable Isotopes

Water samples were collected for stable isotope analyses ($^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/^1\text{H}$) in 30 ml glass vials with a teflon-cone cap to prevent evaporation during storage. After the major ion results were synthesized a selection of samples were shipped to the U. of Arizona (Tucson) isotope laboratory for analysis using standard methods (gaseous CO_2 equilibration for oxygen isotopes; catalyzed reduction to H_2 gas for hydrogen). Results shown in **Table 4** are reported as per mil deviations from the isotope ratios in Vienna Standard Mean Ocean Water (VSMOW), according to the relationships:

$$\delta_{18\text{O}} = \frac{(^{18}\text{O}/^{16}\text{O})_{\text{sample}} - (^{18}\text{O}/^{16}\text{O})_{\text{VSMOW}}}{(^{18}\text{O}/^{16}\text{O})_{\text{VSMOW}}}$$

and

$$\delta_{2\text{H}} = \frac{(^2\text{H}/^1\text{H})_{\text{sample}} - (^2\text{H}/^1\text{H})_{\text{VSMOW}}}{(^2\text{H}/^1\text{H})_{\text{VSMOW}}}.$$

Samples to be analyzed for $^{15}\text{N}/^{14}\text{N}$ ratios in dissolved nitrate were collected in duplicate in 1-liter polyethylene bottles. One bottle was shipped to Magic Labs where, in addition to the suite of major ions, the sample was analyzed for nitrate-N, ammonia and total organic-N concentrations; its duplicate was shipped frozen to the U. of Arizona (Tucson) isotope laboratory. The N-isotope ratio in dissolved nitrate was analyzed using evaporative separation technique to concentrate nitrate as a salt, followed by pyrolysis and analysis of $^{15}\text{N}/^{14}\text{N}$ in the N_2 . Results are reported as per mil deviations from the isotope ratio in air (**Table 4**), according to the relationship:

$$\delta_{15\text{N}} = \frac{(^{15}\text{N}/^{14}\text{N})_{\text{sample}} - (^{15}\text{N}/^{14}\text{N})_{\text{Air}}}{(^{15}\text{N}/^{14}\text{N})_{\text{Air}}}.$$

The standard preparation protocol for extracting and concentrating nitrate-N in water samples involves the use of ion-exchange resins. Evaporative preparation, although non-standard, is a rapid and simple method that can be applied to samples in which nitrate is the sole dissolved nitrogen species. In this study, all samples except one had nitrate representing more than 95 percent of total dissolved nitrogen (**Table 4**); only at site 02 where nitrate concentration was the lowest, did organic-N represent an appreciable fraction of total dissolved nitrogen. Assuming an average isotope ratio of +5 permil for dissolved organic-N (Heaton, 1986) the $^{15}\text{N}/^{14}\text{N}$ ratios reported in **Table 4**, when corrected for their organic-N content, indicated a maximum correction of -0.3 permil at site 02 and negligible corrections in all other samples.

3. Results and Discussion

3.1. Hydrogeology

Cross-sections through the study area, one approximately E-W and the other parallel to the American Falls Reservoir, are shown in **Figures 5a** and **5b**, respectively. In general, the stratigraphy corresponds to that expected for the eastern Snake River Plain aquifer, with variably fractured basalt units intercalated with occasional clay or sandy interbeds; a thick mixed clay, sand and gravel unit encountered in the two deepest wells in cross-section A-A' (**Figure 5a**) is similar to the Raft Formation seen in test borings at the ConAgra site (Coffan, 2003) but is not seen in the two deepest wells in cross-section B-B' (**Figure 5b**). Although the majority of interbeds described in drillers' reports are predominantly clay, it is unlikely that any of these are correlative with the thick, massive clay unit known as the American Falls Lake Bed (AFLB) that is found between about 1330 and 1335 meters above mean sea level (amsl). As shown in **Figure 6**, it probably does not extend westward far enough to be seen except in wells very nearest the reservoir, such as wells 01 and 02 which encounter a sufficiently thick sequence of clayey sediments (**Figure 5b**) and at a depth comparable to that of the AFLB.

Ground-water levels throughout the study area tend to fall within a narrow range corresponding to the range in reservoir levels (dashed blue lines in **Figures 5a** and **5b**, corresponding to 2006-2007's elevation range of 1317-1328 meters amsl). Water levels reported in drillers' logs at the time of drilling (vertical blue bars) are similar to water levels that were measured during this study (arrowheads), with one exception. As shown in **Figure 5b**, well 26's water level at the time of drilling was substantially lower than nearby wells drilled to similar depths. Such a discrepancy is commonly found in drillers' reports, however, when the ground-water level was measured too soon after drilling in an undeveloped or poorly developed well to have allowed the water level to rise to its equilibrium level. Except for well 26, ground-water levels display a consistent pattern, possibly regulated by the reservoir: they vary within the seasonal water-level range that the reservoir experiences. The data also suggest that wells distant from the reservoir tend to have lower ground-water levels than wells near the canals and reservoir, suggesting a westward component to ground-water flow in the study area. This observation is consistent with local ground-water mounding due to canal leakage (C. Holder, 2007, pers. comm.; Poulson, 2004; Coffan, 2003) and, presumably, to reservoir leakage.

Only one proximal well pair (01 and 02) was available to measure the difference in hydraulic head between the shallow and deep aquifers, although shallow/deep hydraulic heads in three other wells located near the reservoir and within 1.5 km of each other could also be compared (wells 06 and 11 measured in October, 2006 and wells 08 and 11, in April, 2007). As can be seen from **Table 1** and **Figures 5a** and **5b**, these three well pairs also exhibit a marked downward vertical gradient, suggesting that the reservoir does recharge the aquifer system.

Clay-rich sedimentary interbeds which segregate the water-bearing basalt into various zones appear to be correlative over distances of four to six kilometers across the study area. One of the most laterally continuous clay units underlies much of the Pleasant Valley shield volcano and Spring Hollow's watershed. The elevation of this interbed relative to Spring Hollow's discharge point (**Figure 5a**) suggests that Spring Hollow is the discharge zone of a perched aquifer that lies

on this interbed. The thickest sedimentary interbeds occur in the phreatic zone in the eastern half of the study area and segregate the basalt aquifer into upper and lower zones at approximately the 1322 m elevation. As noted above, the vertical hydraulic gradient between these zones indicates that they are hydraulically distinct. Subsequent references to "shallow" and "deep" aquifers in this area, therefore, will refer to ground water that is tapped above and below about 1322 meters amsl.

3.2. Water Chemistry

Figures 7a and 7b summarize the spatial and temporal variability of major-ion chemistry along cross-sections A-A' and B-B' respectively. The Stiff plots depict the abundances of major cations and anions in meq/l (as the lengths of the "arms" of each plot) and the concentrations of nitrate on a color-coded scale. Temporal trends are also summarized for those locations that were sampled multiple times between October, 2006 and April, 2007 (multiple Stiff plots shown in chronological order from top to bottom).

Figure 8 shows the geographic distribution of elevated nitrate levels. The highest nitrate concentrations tend to occur in the vicinity of the canal system, although a few moderate nitrate occurrences are found in the upper part of Spring Hollow's watershed (wells 30, 33, 37, 38). The highest nitrate concentrations in this study were observed at Spring Hollow, seep 07, and wells 03, 29 and 34. **Figure 9** depicts the vertical segregation of nitrate levels between shallow and deep ground water, confirming that ground waters above about 1320 meters amsl are far more contaminated than deeper ground waters.

Figure 10 summarizes major ion concentration relationships in a Piper trilinear plot. Two anion mixing trends are apparent: one, associated with Spring Hollow, clearly is associated with higher nitrate concentrations; the other, with the exception of wells 29 and 34, has low to moderate nitrate levels. Both mixing trends show a marked correlation between nitrate, chloride and sulfate (i.e., higher nitrate with increasing Cl and SO₄).

3.3. Influence of Canals

Figure 11 summarizes the water-level data obtained from wells that were measured multiple times. Note that elevations are plotted on a relative scale so that all the data can be shown on one plot and they are not intended to indicate absolute elevations among the measurement sites. The magnitude and timing of the seasonal water-level response is indicated by USGS monitoring well 07S 30E 28BBC1, located approximately 6 miles southwest of the study area. With the exception of well 03, the responses observed in Pleasant Valley appear to be similar, although it must be noted that the USGS well is not influenced by canal seepage like the wells in our study area. The marked difference in well 03's response can be explained by its proximity to a major canal (approximately 100 meters away) and its very shallow completion depth. The well encounters basalt at about 20 ft below land surface and terminates in fractured basalt; according to the owner, it responds very rapidly when the canal fills in the spring. Although we did not take measurements in April to confirm this at well 03, other wells whose water levels were

measured immediately prior to and after the canals came in (wells 11, 32, 41) did respond, albeit much less dramatically. Well 03's hydrograph, then, is a recession curve in response to the local water table's decline as the canal goes dry in the fall.

Figure 12a and **12b** summarize the chemical and isotopic responses observed at four sampling sites in response to the canals going out in the fall and coming in again in the spring. Spring Hollow's response is artificially exaggerated because canal water flows directly into the estuary at the sampling point, and it is impossible to avoid dilution of samples during the irrigation season. Well 03's response is the strongest of any well, because of the magnitude of the effect that canal leakage has on the water table at this location. In both cases, the dilution effect is seen in major ions and stable isotopes. In contrast, geochemical responses are non-existent in deep wells such as well 26 and in some shallow wells like well 21, which is almost the same depth as well 03 and even closer to a major canal, presumably because an individual well's construction and surface seal dictate how sensitive the well is to seasonal canal dilution or that canals are variably leaky, so that not all shallow wells that are near canals will respond in the same way (S. Howser, Aberdeen-Springfield Canal Co., 2007, pers. comm.).

Because dilution by infiltrating canal seepage can dilute contaminants, ground-water quality surveys should not be carried out during the irrigation season in areas affected by canals. This is especially true of Spring Hollow's historically high nitrate levels. **Figure 12c** combines historic nitrate concentration data (**Figure 2**) with the new data collected during this study. Examining the lowest nitrate values (like the sample collected May 21, 2007) it is apparent that all low values occur during or near the beginning or end of the irrigation season and that the majority of the highest values were observed outside the irrigation season. The regression trend shown in **Figure 12c** is based only on the highest nitrate values. Although the trend suggests a gradual decrease in nitrate concentration with time, the slope of the regression is not significant at a 95% confidence level and so it must be concluded that Spring Hollow's nitrate levels are not decreasing over time.

3.4. Water Source Identification

The stable isotopes of oxygen and hydrogen in water are some of the most-used tracers in hydrology. Their systematic variation in the water cycle in response to temperature and altitude, air mass movement and the differential concentration they experience during evaporation make them useful in a wide range of water-source characterization and mixing problems (Faure, 1986). **Figure 13** summarizes the stable isotope data in the context of local meteoric variations in a so-called meteoric water plot, in relation to waters in and on the eastern Snake River Plain. Almost all global precipitation plots on a meteoric water line (MWL) with a slope approximately equal to 8.0 (Craig, 1961). Locally, the MWL's intercept is offset in response to local high-altitude orographic effects, topography in the prevailing upwind direction, and the sources of moisture responsible for the air masses that sustain local precipitation. Precipitation that recharges a ground-water flow system is isotopically "labeled" by these effects. More importantly, water is characteristically "relabeled" by differential isotopic enrichment when it evaporates. The result is that points plot farther to the right of the MWL as evaporation proceeds, with a slope of 5 to 7 depending on local conditions.

The data shown in **Figure 13** illustrate all of these effects. The MWL for eastern Idaho (Benjamin et al., 2004) extends over the range of surface- and ground-water variability in the region. Samples of deep, regional ground water collected at the Idaho National Laboratory (Ott et al., 1994) cluster close to the MWL, pointing to their derivation from recharge that did not experience evaporation; in contrast, three samples of shallow ground water plot far to the right of the MWL and clearly indicate they were recharged by standing water that had been subjected to evaporative enrichment. Note that most ground waters from the eastern Snake River Plain fall on a line having a slope between the MWL and the evaporative enrichment line (Wood and Low, 1988), suggesting that ground water in this region is either derived from multiple sources (having local MWLs of different intercept in the highlands north and south of the Plain) or from mixtures of directly recharged (non-evaporated) snowmelt and partially evaporated surface water (like some Big Lost river waters).

The clustering of Pleasant Valley isotope values in **Figure 13** suggests three groupings of waters:

- (i) the most ^{18}O and ^2H depleted waters, plotting near the deep, regional ground water field;
- (ii) intermediate waters, plotting near but slightly to the right of the aquifer trend line; and
- (iii) the most ^{18}O and ^2H enriched waters, clearly indicative of evaporative enrichment.

In the case of evaporatively labeled waters, it is particularly useful to examine the coupled enrichments of stable isotopes and solutes such as chloride and other conservative tracers. Since evaporation produces a proportional enrichment in both ^{18}O and ^2H , only one isotope need be considered. Crossplots of chloride vs. ^{18}O and nitrate vs. ^{18}O are shown in **Figure 14**. Because of the absence of reduced, redox-sensitive species such as ammonium, nitrate is assumed to behave conservatively in these ground waters (see Section 2.5). Waters from groups (ii) and (iii) display systematic chloride and nitrate variations, with consistently higher NO_3/Cl ratios than group (i) waters and with the highest NO_3 , Cl and SO_4 concentrations in the most evaporatively enriched group (iii) waters. However, these highly elevated anion concentrations cannot be due to evaporative enrichment alone, for the isotopic enrichments would be far greater. Such solute-enriched ground waters, therefore, must have been contaminated after experiencing evaporation. The dashed lines in **Figure 14** depict mixing relationships between a solute-enriched end member (Spring Hollow) and a dilute end member (canal water); well 03 appears to be a mixture of canal and Spring Hollow water.

As was shown in **Figure 10**, wells 29 and 34 are chemically distinct from well 03 and Spring Hollow. Although they are not obviously related by mixing to any other water, **Figure 14** clearly shows that wells 29 and 34 are a group (ii) water, affected by canal water and possibly minor evaporation. On the basis of the above evidence, four water types can be discriminated on the basis of their oxygen isotope ratios and anion contents:

- (i) non-evaporated deep ground water ($\text{Cl}/\text{NO}_3\text{-N} > 15$, by mass);
- (ii) shallow, canal-influenced ground water, with minor evaporation ($\text{Cl}/\text{NO}_3\text{-N} < 10$);
- (iii) high-solute ground water, with significant evaporation (highly contaminated); and
- (iv) canal water (very low solutes; variable evaporative enrichment).

Figure 15 shows geographic locations of where group (i) waters occur and whether a well taps the shallow or deep aquifer (where drillers' logs were available). Because of the difficulties in

reliably matching drillers' reports to old wells, only those sites that could be unambiguously classified are shown. For the most part, the geochemically-classified occurrences of deep, regional ground water coincide with samples collected from wells completed in the deep aquifer (below 1322 meters amsl; see section 3.1), thereby lending support to the geochemically based classification system and the hypothesis that a distinct water type is associated with the regional flow system. **Figure 16** provides further corroboration of the classification: All but two group (i) waters plot on one anion mixing line (high Cl/SO₄), and all but two group (ii) waters plot on the other anion mixing line (high SO₄/Cl).

3.5. Nitrate Source Discrimination

Just as stable isotopes are invaluable tracers of water's provenance, so can they be used to identify the sources of certain solutes. Stable isotopes of S, C, and N, especially, have been shown to be useful in this regard (Faure, 1986). **Figure 17** summarizes the general ranges of N¹⁵/N¹⁴ ratios in precipitation, inorganic fertilizers, and organic-N in soil, ground water and organic wastes (Heaton, 1986). However, unlike the situation with the isotopes of water, dissolved nitrogen species can be chemically and/or biochemically active and may undergo multiple chemical transformations during transit through an aquifer. Because isotopic shifts (fractionations) occur during each such transformation, the solute's isotopic "label" can be altered, potentially obscuring its original isotopic ratio and, hence, origin.

In the case of nitrate, it has been shown that ¹⁵N/¹⁴N ratios (or δ values relative to air-N) can, in many ground-water environments, be a fairly reliable tracer of the origin of the dissolved nitrate-N (Bolhke and Denver, 1995; Kreitler and Browning, 1983). However, in the wrong hydrogeochemical setting, the N-isotope ratio of dissolved nitrate is subject to change by confounding effects (Spalding and Exner, 1991). For example, in the simplest situation, an inorganic fertilizer such as KNO₃ releases its nitrogen via dissolution and the ¹⁵N/¹⁴N ratio of the resulting dissolved phase, in the absence of microbial or other redox transformations, remains identical to that of the original solid phase. In a fertilizer such as ammonium nitrate (NH₄NO₃), however, the ¹⁵N/¹⁴N ratios of ammonia-N and nitrate-N differ and can change (fractionate) at different rates during chemical transformations following dissolution. In an oxygen-rich soil zone or shallow aquifer, half of the original nitrogen (as nitrate-N) would be redox-stable and would not undergo any chemical transformation, whereas the ammonia-N fraction would be redox-active and readily transform to NO₃⁻ or N₂ depending on local redox conditions, microbial populations and mineral substrates. If the original ammonia fraction were completely transformed to NO₃⁻, its ¹⁵N/¹⁴N ratio would be unchanged and the resulting N-isotope ratio of dissolved nitrate would be the same as the original bulk fertilizer. If the ammonia fraction were converted to N₂ instead, in a process known as denitrification, the resulting nitrogen would be lost and the ¹⁵N/¹⁴N ratio of the remaining nitrate fraction would differ from the original fertilizer's bulk isotope composition. **Figure 17** shows the direction of the N-isotope shift that accompanies denitrification, a process that can lead to unusually low nitrate concentrations and large N¹⁵ enrichments in the residual nitrate. Transformation reactions involving organic sources and the complex micro-redox environments commonly found in organic-rich substrates are even more problematic to decipher, so that discriminating between human and animal waste sources on the basis of ¹⁵N/¹⁴N ratios should be conducted with caution.

In shallow, oxygen-rich aquifers, nitrate is chemically stable and behaves quasi-conservatively, so that limited distinctions can be made on the basis of $^{15}\text{N}/^{14}\text{N}$ ratios alone; for example, between organic- (waste derived) and inorganic (fertilizer derived) nitrogen (Baldwin and Cook, 2004; Howarth, 1999; Seiler, 1996). Of the nitrate sources shown in **Figure 17**, organic waste-derived nitrogen and inorganic fertilizer-derived nitrogen are the most common sources that are associated with high levels of nitrate contamination in ground water.

Figure 18 summarizes the N-isotope and N-concentration data of **Table 4**, where the N-isotope ratios have been corrected for possible analytical interference by organic-N (Section 2.5). Based on the classification shown in **Figure 16**, nitrate samples are color-coded, indicating their origin from deep (regional, group i) or shallow (canal- and evaporation-affected, group ii) ground water. The most obvious trends reveal the involvement of two end-members having different N-isotope compositions: one (in well 03), toward higher $^{15}\text{N}/^{14}\text{N}$ ratios and the other (Spring Hollow), toward lower $^{15}\text{N}/^{14}\text{N}$ ratios. To investigate possible mixing relationships involving these end members, however, the data must be replotted in $\delta^{15}\text{N}$ vs. $1/\text{concentration}$ space (Faure, 1986) because the isotopic composition of a dual-phase mixture (e.g., a nitrate salt added to ground water) does not define a straight line in $\delta^{15}\text{N}$ vs. concentration space.

Figure 19 shows the same data plotted as $\delta^{15}\text{N}$ vs. $1/[\text{nitrate-N}]$. Possible contaminant sources plot at 0.0 on the x-axis, where mixing relationships between background nitrate and contaminant sources plot along straight lines. Chemical transformations (such as denitrification) plot as curvilinear trends. The hachured rectangle in the diagram represents background nitrate with $\delta^{15}\text{N}$ values near +5 permil and nitrate-N concentrations between about 2 and 3 mg/l. All but one deep-well sample (well 02) plots within this background field. Well 02's elevated $^{15}\text{N}/^{14}\text{N}$ ratio, coupled with its low nitrate concentration, is consistent with a process of denitrification.

The $\delta^{15}\text{N}$ ranges of nitrate derived from inorganic fertilizer and organic waste are shown as vertical yellow bars that extend to lower and higher $\delta^{15}\text{N}$ values, respectively, of inorganic fertilizer and organic waste-derived nitrogen sources. Two different linear trends (dashed arrows) implicate inorganic fertilizer as the primary source of nitrate in well 12 and Spring Hollow, as well as in wells 01, 27, and 29. In contrast, wells 03 and 34 do not define a two-component mixture between background nitrate and either a ^{15}N -enriched organic source or a ^{15}N -depleted inorganic source. Rather, these wells appear to represent multi-component mixtures in which both septic and/or animal waste and fertilizer are contributing to nitrate contamination.

3.6. Sources of Nitrate Contamination

3.6.1. Shallow ground water

Fertilizer appears to be a more common source of nitrate contamination in Pleasant Valley than are animal or human wastes, if the samples collected in this study are representative of the type and spatial distribution of contaminant sources in the area. Two-thirds of the samples with elevated nitrate levels that were analyzed for N-isotopes contain nitrate of primarily fertilizer

origin. Nitrate contamination at Spring Hollow appears to be derived solely from fertilizer; in addition, its chloride and stable isotope content indicate its waters have experienced significant evaporation. Spring Hollow's stratigraphic position relative to a shallow, clay-rich aquitard (**Figure 5a**) suggests that it is a discharge point for a perched aquifer that intercepts moisture originating over its watershed; a handful of flow measurements made between 1998 and 2002 indicate that Spring Hollow discharges approximately 250-400 gpm, year around (N. Poulson, written comm., 2007), a flow rate that could be supported by only 0.002 inches of annual precipitation or sprinkler irrigation not intercepted by the root zone. In light of these considerations, it is likely that sprinkler irrigation is the mechanism responsible for transporting fertilizer-derived nitrate to Spring Hollow's water via a shallow, perched aquifer.

After Spring Hollow, well 12 is the clearest example of a fertilizer-contaminated source, with nitrate plotting on an isotopic mixing line between Spring Hollow and background (**Figure 19**). This is surprising, because well 12 is fairly deep (225 ft). However, the well is only cased to 159 ft and perforates the clay aquitard that supports the perched aquifer feeding Spring Hollow; its elevated $\delta^{18}\text{O}$ clearly indicates it is group (ii) water, affected by evaporation. Its high dissolved nitrate concentration and ^{15}N systematics further suggest that a poor casing seal permits leakage of perched water (evaporated and fertilizer-contaminated) to mix with deep ground water in this well.

The remainder of wells analyzed for N-isotopes either represent a mixture of background nitrate and fertilizer-derived nitrate or a three-component mixture of organic waste-derived N, fertilizer-N and background nitrate-N. For example, well 03 and 34 do not plot on a simple two-component mixing line between background nitrate and organic waste (**Figure 19**). If the $\delta^{15}\text{N}$ of fertilizer-derived nitrate in the study area lies between about 0 (the mid-range shown in **Figure 17**) and +4 permil (an average of the end members of the two mixing trends involving fertilizer in **Figure 19**), and if nitrate derived from organic waste ranges between +10 and +20 permil, then well 03's nitrate comprises between 40 to 80 percent of fertilizer-derived nitrogen. All other three component mixtures comprise an even larger fraction of fertilizer-derived nitrate.

Crossplots of nitrate vs. chloride and sulfate vs. chloride are shown in **Figures 20a** and **20b**, respectively, classified according to water type (group i or ii) and nitrate source (fertilizer or organic waste). All but one site classified as group (i) water are characterized by ionic signatures very similar to domestic septic effluent that has been documented in the lower Portneuf Valley (Meehan, 2005). Although well 03 and Spring Hollow are clearly different, their NO_3/Cl and SO_4/Cl ratios are nearly identical yet their dissolved nitrate contents apparently reflect different amounts of organic waste-derived nitrogen relative to fertilizer-derived nitrogen. Spring Hollow's nitrate appears to almost entirely originate from fertilizer, whereas well 03 reflects a mixture of fertilizer-N with no more than 60 percent derived from organic waste. The small but consistent difference between SO_4/Cl ratios in well 03 and in Spring Hollow supports the hypothesis that well 03 is a mixture of organic- and fertilizer-derived nitrate, with most of its nitrate and major ionic constituents derived from a source like Spring Hollow's. Although wells 29 and 34 also tap a source of organic-derived nitrate, their anionic ratios are very different from well 03's and, like almost all group (i) waters, their anionic ratios are very similar to domestic septic effluent.

The conclusion is that domestic septic effluent is the source of nitrate in wells 29 and 34 but not in well 03. In light of the latter's shallow completion depth and proximity to a small cattle feedlot, plus anecdotal evidence from the well's owner that snowmelt and rainfall in the feedlot disappear into the subsurface very rapidly, we conclude that much of well 03's dissolved nitrate derives from organic waste of an animal origin. The high proportion of fertilizer-N in this well and its shallow depth suggest that well 03 reflects a perched aquifer situation similar to the one that supports Spring Hollow's discharge.

A significant fraction of the nitrate in wells 29 and 34 also appears to originate from a fertilizer source (**Figure 19**) but their anion ratios indicate that the organic fraction is of septic, rather than of manure, origin.

3.6.2. Deep ground water

All samples with elevated nitrate levels in **Figure 19** represent group (ii) ground water that are derived from the shallow aquifer (i.e. canal- and/or evaporation-affected). Fertilizers and organic waste are the predominant sources of nitrate in the study area and, since both sources originate at or near the land surface, they would be expected to have the greatest impact on shallow ground water. The origin of nitrate in deep (group i) ground water, however, is less obvious. As discussed in Section 3.4 group (i) waters are unaffected by evaporation or canal seepage (**Figure 14**), are found mostly in wells known to tap the deeper aquifer (**Figure 15**), and are almost exclusively associated with the low-SO₄/Cl mixing trends shown in **Figure 16** and **Figure 20b**. Furthermore, their cationic ratios are significantly less variable than group (ii) waters (**Figure 16**) and their anionic ratios group more tightly about their mixing lines (**Figures 20a** and **20b**). Finally, all samples of group (i) water but one have nitrate concentrations that are within background for this area (< 2.6 mg/l nitrate-N).. The evidence suggests two possibilities for the origin of nitrate in group (i) water:

- (a) upgradient contamination (point or non-point sources) introduced into the regional flow system and geochemically homogenized during transport over some distance; or
- (b) localized point-source contamination introduced to the deep aquifer via vertical migration and that is somehow geochemically homogenized.

As noted in Section 3.1, strong vertical hydraulic gradients exist near American Falls Reservoir, so that downward migration of shallow ground water and locally-derived contamination occurs in at least some wells (e.g., well 12, Section 3.6.1). Vertical movement may occur along well casings with leaky seals, in abandoned or improperly plugged wells, or along other natural and artificial vertical pathways. For example, well 12 demonstrates how contamination from a shallow aquifer can provide a point source input to the deep aquifer. If there are many such wells in the study area, then different vertical zones in the deep aquifer would be contaminated to varying degrees with different geochemical signatures depending on the depths of penetration of the point-source wells, the magnitude of the local vertical hydraulic gradient, and perhaps local pumping rates. If many such point sources contribute septic effluent with anion ratios as variable those seen in wells 29 and 34 (**Figures 20a** and **20b**), then their remarkably constant chloride/nitrate and chloride/sulfate ratios must involve some mechanism for homogenizing the chemical signatures in the deep aquifer. This could be achieved in two ways: by diluting a group

(ii) end-member water to varying degrees with canal or reservoir water; or by homogenizing the shallow ground-water inputs prior to contaminant migration into the deep aquifer.

It is unlikely that deep ground water experiences seasonal dilution by canal water, as all the evidence collected in this study indicates that seasonal impacts on deep ground-water composition are insignificant (e.g., **Figure 12b**). However, the effect of American Falls Reservoir's water level fluctuations on local ground-water dynamics and water quality is unknown. For example, is it simply coincidence that high nitrate concentrations are restricted to a depth range equivalent to the minimum water level in American Falls Reservoir (**Figure 9**)? If the reservoir is a significant source of recharge to the local ground-water system, it is possible that the dynamic, seasonal nature of this recharge homogenizes the shallow ground water that does make its way to the deep aquifer.

Alternatively, the septic-like anion signature observed in deep ground water may reflect effluent derived from shallow aquifers many kilometers upgradient of the study area. Shallow aquifers across the Snake Plain are commonly contaminated with nitrate (Parlman, 2002) and nitrate-contaminated ground water has been documented in several areas upgradient of Pleasant Valley (Meachum, 1999). An examination of a regional-scale ground-water isopotential map suggests that flow paths terminating in the Pleasant Valley area originate in the Ucon-Osgood area of the upper Snake Plain (Lindholm et al., 1987); these flow paths underlie irrigated lands (containing domestic septic as well as other potential nitrate sources) in an area north and west of Aberdeen, west of Rockland, and in the Osgood-Ucon-Idaho Falls area. However, exact flow path trajectories cannot be determined with any confidence, so it is difficult to say exactly how many potential upgradient septic point sources are hydraulically upgradient of the Pleasant Valley study area. Shallow septic-derived contamination could find its way into the regional flow via localized (point-source) pathways or it could merge with the regional flow as non-point source plumes in response to flow system dynamics. Either way, long-distance transport would be expected to homogenize the geochemical signatures of multiple sources having different anion ratios.

Whether locally or regionally derived, transport of contaminants in the eastern Snake River Plain aquifer occurs via preferential flow in fractures, lava tubes and contacts between basaltic lava units (Lindholm and Vaccaro, 1988; Welhan et al., 2002). Solutes that move with ground water along such "fast paths" experience minimal longitudinal dispersion during horizontal flow, even over tens of kilometers (Cecil et al., 2000), so that different vertical zones in the deep aquifer could reflect distinctly different geochemical signatures depending on the sources from which they ultimately derive (Frederick and Johnson, 1995). No matter how geochemically heterogeneous the deep aquifer may be, however, whether due to localized vertical contaminant migration or horizontal flow along multiple, regional-scale "fast paths", any hydrostratigraphic differences would tend to be homogenized during pumping. Wells that are open over large vertical intervals allow water from distinct zones in the aquifer that may be compositionally different to mix when pumped. A sample collected in this manner represents water from different zones which, in turn, represent different fast paths in the aquifer; a mixture of water from these zones would be indistinguishable from ground water that has experienced significant dispersive mixing (Robertson, 1974).

Insufficient information is available at this time to determine whether the apparent homogeneity of ionic ratios in group (i) waters is a sampling artifact; hence, a distinction between hypotheses (a) and (b) is premature at this time. Regardless of the specific mechanism of geochemical homogenization, however, it is clear that deep ground water in Pleasant Valley is being affected by contamination derived from near-surface sources. Whether the nitrate in group (i) waters originates locally or from one or more distant, upgradient sources, the inescapable conclusion is that domestic septic effluent exerts a measurable impact on the water quality of the deep aquifer, even in this fast-flowing aquifer. A similar conclusion was reached in the nearby lower Portneuf River Valley aquifer where septic effluent is the dominant source of nitrate, sulfate and chloride (far exceeding the impact of other potential sources such as winter road salting), and where the cumulative impact of hundreds of septic drain fields degrades water quality despite extremely high ground-water flow velocities (Meehan, 2005).

4. Conclusions

- Two major limitations encountered during this study were (i) identifying well locations that correspond to available well logs, and (ii) reliable access to wells to collect ground-water level data.
- The basalt aquifer system is vertically segregated by clay-rich sedimentary interbeds some of which are correlated over distances of several kilometers and which provide a measure of protection to the deeper aquifer from surface-water and/or shallow ground-water contamination; the stratigraphic distinction between "shallow" and "deep" ground water is made at about 1322 m amsl.
- All wells in the study area are completed as open holes in basalt, with only their casings providing protection against shallow ground-water contamination from local point-source (septic and manure) inputs.
- Shallow ground water consistently has elevated nitrate relative to deep ground water, with locally very high levels; various mechanisms and sources may be responsible for introducing contamination to the shallow aquifer.
- Shallow ground water displays seasonal dilution and water level changes in response to canals filling and draining; the effect in individual wells is variable, likely depending on a well's completion and casing depths, integrity of its surface seal, proximity to canals and canal leakance.
- Ground water can be classified into four types on the basis of anion ratios, nitrate and chloride content, O- and H-isotopes, and its hydrogeologic context:
 - (i) nonevaporation-affected regional ground water (slightly nitrate contaminated)
 - (ii) evaporation- and canal-affected shallow ground water (variably contaminated)
 - (iii) nitrate-rich, evaporation-affected shallow ground water (highly contaminated)
 - (iv) canal-delivered surface water (uncontaminated).

- Spring Hollow water has been significantly affected by evaporation and has very high concentrations of sulfate and chloride relative to deep ground water. Sprinkler irrigation therefore appears to be the most likely mechanism responsible for transporting nitrate applied as fertilizer. However, this hypothesis cannot be tested until additional shallow wells are located and the perched aquifer whose discharge supports Spring Hollow can be sampled directly.
- Major anion ratios distinguish two nitrate-rich end members:
 - (1) a chloride-rich nitrate source, with septic-like anion ratios (e.g., wells 29, 34); and
 - (2) a sulfate-rich source having nonseptic-like anion ratios that is only seen in shallow ground waters affected by evaporation (e.g. Spring Hollow, well 12, well 03).
- N-isotopes of nitrate were used to identify two isotopically different nitrate sources:
 - (1) a ^{15}N -depleted fertilizer source (Spring Hollow) associated with water that is evaporated;
 - (2) two ^{15}N -enriched sources derived from organic waste having different anionic ratios:
 - a sulfate-enriched source associated with feedlot runoff (well 03)
 - a chloride-rich source, having Cl/NO_3 and Cl/SO_4 that are very similar to domestic septic effluent; this source, which occurs only in deep ground and has very uniform anionic ratios that reflect homogenization during ground-water transport; whether its source is local or regional in origin, it is clear that septic effluent is managing to migrate into the deep aquifer and impact water quality.

5. Recommendations

- Confirm and extend the conclusions of this study by analyzing more nitrate samples for their N-isotope ratios and developing a statistical estimate of the proportion of wells that are contaminated predominantly by fertilizer and by organic-waste.
- Locate and sample more shallow wells in or near the Spring Hollow watershed to test the hypothesis of a shallow perched aquifer whose ground water has experienced significant evaporation during sprinkler irrigation and nitrate contamination from fertilizer chemigation.
- Examine other trace constituents of Spring Hollow's water that could confirm a chemigation source (e.g., herbicides, pesticides).
- Document the types and amounts of fertilizer used by farmers in the Spring Hollow watershed, construct a mass balance for fertilizer-derived nitrogen (as well as chloride and sulfate), and compare to the amount of nitrate-N, chloride and sulfate found in Spring Hollow's discharge. Constrain the mass balance using O- and H-isotope labeling, and determine whether sprinkler chemigation is a viable hypothesis to explain Spring Hollow's contaminant source.

6. References

- Baldwin, J.A. and Cook, M.J., 2004, Environmental isotope studies of waste water and ground water at waste water land treatment sites in Idaho; Idaho Dept. of Environmental Quality, Ground Water Quality Technical Report No. 19, 34 pp.
- Benjamin, L., Knobel, L.L., Hall, L.F., Cecil, L.D. and Green, J.R., 2004, Development of a local meteoric water line for southeastern Idaho, western Wyoming, and south-central Montana; U.S. Geological Survey, Scientific Investigations Rept. 2004-5126, 17 pp.
- Bohlke, J.K. and Denver, J.M., 1995, Combined use of groundwater dating, chemical and isotopic analyses to resolve the history and fate of nitrate contamination in two agricultural watersheds, atlantic coastal plain, Maryland; Water Resources Research, v.31, pp. 2319-2339.
- Castelin, P.M., 1974, Water resources of the Aberdeen-Springfield area, Bingham and Power Counties, Idaho; Idaho Dept. of Water Administration, Water Information Bulletin 36, 33 pp.
- Cecil, L.D., Welhan, J.A., Green, J.R., Frape, S.K. and Sudicky, E.R., 2000, Use of chlorine-36 to determine regional-scale aquifer dispersivity, eastern Snake River Plain aquifer, Idaho; Nuclear Instruments and Methods in Physics Research B, v.172, pp. 679-687.
- Coffan, R., 2003, Hydrogeologic investigation at ConAgra American Falls facility pond system; unpubl. progress report; Cascade Earth Sciences, Pocatello, Idaho.
- Craig, H., 1961, Isotopic variations in meteoric waters; Science, v. 133, pp. 1702-1703.
- Faure, G., 1986, Principles of Isotope Geology; Wiley and Sons, NY, 2nd ed., 589 pp.
- Frederick, D.B. and Johnson, G.S., 1995, Estimation of hydraulic properties and development of a layered conceptual model for the Snake River Plain aquifer at the Idaho National Engineering Laboratory, Idaho; Idaho INEL Oversight Program, Idaho Falls, Idaho, 66 pp.
- Heaton, T. H. E., 1986, Isotopic studies of nitrogen pollution in the hydrosphere and atmosphere: a review; Chemical Geology, v. 59, p.87-102.
- Houser, B.B., 1994, Quaternary stratigraphy of an area northest of American Falls Reservoir, eastern Snake River Plain, Idaho; in Link, P.K., Kuntz, M.A. and Platt, L.B. (eds.), Regional Geology of Eastern Idaho and Western Wyoming, Geological Society of America Memoir 179, pp. 269-288.
- Howarth, R.B., 1999, Assessment of sources of elevated nitrate in ground water in northwest Ada County, Idaho, using environmental isotopes; Ground Water Quality Technical Report No. 11, Idaho Division of Environmental Quality, 61 pp.

IDWR, 2007, Idaho Department of Water Resources well construction database, <http://www.idwr.idaho.gov/water/well/search.htm>

Inside Idaho, 2007, Interactive Numeric and Spatial Information Data Engine; University of Idaho, <http://inside.uidaho.edu/>

Kreitler, C.W. and Browning, L.A., 1983, Nitrate-isotope analysis of groundwater nitrate in carbonate aquifers: natural sources versus human pollution; *Journal of Hydrology*, v.61, pp. 285-301.

Lindholm, G.F. and Vaccaro, J.J., 1988, Region 2, Columbia Lava Plateau, in Back, W. Rosenshan, J.S. and Seabar, P.R., eds., *Hydrogeology: Boulder, Colorado*, Geological Society of America, *Geology of North America*, v. O-2, *Decade of North American Geology*, p. 37-50.

Lindholm, G.F., Garabedian, S.P., Newton, G.D., and Whitehead, R.L., 1987, Configuration of the water table and depth to water, spring 1980, water level fluctuations, and water movement in the Snake River Plain regional aquifer system, Idaho and eastern Oregon: U.S. Geological Survey Hydrologic Investigations Atlas HA-703, scale 1:500,000, 1 sheet.

Meachum, Teresa, 1999, Nitrates in groundwater—study of levels in southeast Idaho: Idaho Falls, University of Idaho, unpublished M.S. thesis, 48 pp.

Meehan, C.W., 2005, Geochemistry of the southern Pocatello aquifer and its implications for aquifer recharge and contamination potential; unpubl. M.S. thesis, Idaho State University, 202 pp.

Neely, K.W., 2005, Nitrate Overview for the Statewide Ambient Ground Water Quality Monitoring Program, 1990 – 2003; Ground Water Quality Technical Brief, Idaho Department of Water Resources, http://www.idwr.idaho.gov/hydrologic/info/pubs/gwq/nitrate_1991-2003.pdf

Ott, D.S., Cecil, L.D. and Knobel, L.L., 1994, Stable isotopes of hydrogen and oxygen in surface water and ground water at selected sites on or near the Idaho National Engineering Laboratory, Idaho; U.S. Geological Survey, Open-File Rept. 94-55, 14 pp.

Parlman, D.J., 2002, Analysis of Nitrate (NO₃⁻ Concentration Trends in 25 Ground Water Quality Management Areas, Idaho, 1961–2001; U.S. Geological Survey Water Resources Investigations Report 02-4056, 60 pp.

Phillips, W.M. and Welhan, J.A., 2006, Geologic Map of the Idaho Falls North Quadrangle, Bonneville County, Idaho, 1:24000; Idaho Geological Survey, [http://www.idahogeology.org/PDF/Digital_Data_\(D\)/Digital_Web_Maps_\(DWM\)/ifnorth-DWM-77-M.pdf](http://www.idahogeology.org/PDF/Digital_Data_(D)/Digital_Web_Maps_(DWM)/ifnorth-DWM-77-M.pdf)

Poulson, N., 2004, Geologic characterization near Spring Hollow, Power County, Idaho; unpubl. report, Environmental Engineering Program, Idaho State University.

Robertson, J.B., 1974, Digital modeling of radioactive and chemical waste transport in the Snake River Plain aquifer at the National Reactor Testing Station, Idaho; U.S. Geological Survey, Water Resources Division, IDO-22054, Idaho Falls, Idaho.

Scott, W.E., Pierce, K.L. Bradbury, J.P. and Forester, R.M., 1982, Revised Quaternary stratigraphy and chronology in the American Falls area, southeastern Idaho; in Bonnichsen, B. and Breckenridge, R.M. (eds.), *Cenozoic Geology of Idaho*; Idaho Bureau of Mines and Geology, Bulletin 26, pp. 581-595.

Seiler, R. L., 1996, Methods for Identifying Sources of Nitrogen Contamination of Groundwater in Valleys in Washoe County, Nevada; U.S. Geological Survey, Open-File Report 96-461, 20 p.

Spalding, R.F., and Exner, M.E., 1991, Nitrate contamination in the contiguous United States. In: I. Bogardi and R.D. Kuselka (editors), *Nitrate Contamination*; Springer, Berlin, pp 13-48.

Wassenaar, L., 1995, Evaluation of the origin and fate of nitrate in the Abbotsford Aquifer using the isotopes of ^{15}N and ^{18}O in NO_3^- ; *Applied Geochemistry*, v.10, pp. 391-405.

Welhan, J.A., Johannesen, C.M., Reeves, K.M., Clemo, T.M., Glover, J.A. and Bosworth, K.W., 2002, Morphology of inflated pahoehoe lavas and spatial architecture of their porous and permeable zones, eastern Snake River Plain, Idaho; in Link, P.K. and Mink, L.L. (eds.), *Geology, Hydrogeology and Environmental Remediation: Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho*; Geological Society of America Special Paper 353, pp. 135-150.

Welhan, J., Meehan, C. and Reid, T., 1996, The lower Portneuf River valley aquifer: a geologic / hydrologic model and its implications for wellhead protection strategies; Final Report, EPA Wellhead Protection Demonstration Program, Idaho State University, 48 pp.

Wood, W.W. and Low, W.H., 1988, Solute geochemistry of the Snake River Plain regional aquifer system, Idaho and Oregon; U.S. Geological Survey, Prof. Paper 1408-D, 79 pp.

Tables

Table 1. Static water level measurements made during this study. "Tape" refers to electrical conductance measurements; "sonic" to measurements taken with the ultrasonic time-of-travel method.

Table 2. Duplicate samples collected for quality assurance evaluation of water quality data.

Table 3. All water quality sampling results organized by site number and sampling date.

Table 4. Summary of all stable isotope data collected, sorted by sample site.

Figures

- Figure 1. Study area showing extent of irrigated land, principal hydrographic features, and approximate extent of the sampled area (yellow boundary).
- Figure 2. Elevated nitrate-N concentrations in Spring Hollow's natural seep, based on previously unpublished data (N. Poulson, written communication).
- Figure 3. Location of sampling sites, showing site numbers. Polygon indicates approximate geographic extent of the watershed that may support Spring Hollow's perennial flows.
- Figure 4. Locations where drillers' logs were available, showing sampling site numbers. Filled rectangles are locations of water-level measurements.
- Figure 5a. Subsurface stratigraphy of the study area based on drillers' logs along section A-A'.
- Figure 5b. Subsurface stratigraphy of the study area based on drillers' logs along section B-B'.
- Figure 6. Known extents of the American Falls Lake Bed (AFLB) clay unit.
- Figure 7a. Vertical distribution of nitrate and major ion concentrations, summarized as Stiff diagrams, along cross-section A-A'.
- Figure 7b. Vertical distribution of nitrate and major ion concentrations, summarized as Stiff diagrams, along cross-section B-B'.
- Figure 8. Geographic distribution of nitrate-N concentrations, in mg/l, observed in this study.
- Figure 9. Vertical distribution of elevated nitrate concentrations relative to elevation range seen in the reservoir.
- Figure 10. Variations in major ion chemistry, showing relationship between mixing trends and elevated nitrate-N concentrations in Cl- and SO₄-rich end members.
- Figure 11. Relative static water level trends observed during this study.
- Figure 12a. Variations in major ion chemistry of selected wells and Spring Hollow.
- Figure 12b. Variations in stable isotope ratios of selected wells and Spring Hollow, in response to canal draining (down arrow) and filling (up arrow).
- Figure 12c. All available nitrate concentration data for Spring Hollow, relative to approximate duration of irrigation seasons (vertical blue bars).
- Figure 13. Stable isotope composition of Pleasant Valley waters compared to that of the eastern

Snake Plain in general.

Figure 14. Classification of ground water sources based on chloride, nitrate and O^{18} content.

Figure 15. Geographic locations of wells affected by evaporation and/or mixing with canal seepage on the basis of their chloride and stable isotope contents.

Figure 16. Deep regional ground waters (group i) define an anion mixing trend that is separate from waters that are slightly affected by evaporation-canal seepage (group ii)..

Figure 17. Nitrogen-isotope ratios that characterize common nitrate sources, after Heaton (1988)

Figure 18. Relationship between δN^{15} of dissolved nitrate and concentrations of nitrate and organic-nitrogen in selected samples collected in April, 2007.

Figure 19. Nitrate mixing and source relationships inferred from N-isotope data.

Figure 20a. Nitrate vs. chloride plot showing waters classified on the basis of anionic ratios, N-isotopes, chloride and oxygen-isotope data.

Figure 20b. Sulfate vs. chloride plot showing waters classified on the basis of anionic ratios, N-isotopes, chloride and oxygen-isotopes.

Appendix A

Sampling and Analytical Information

Sampling sites were chosen based on location, availability of well logs and whether or not permission could be obtained from the owners to sample water and measure water depth. In the case of irrigation wells, water samples were collected only when the pumps were running and crops were being irrigated. Samples were collected as close to the pump as possible. In the case of domestic wells, water was flushed from the spigot for at least 30 seconds. Sample bottles were supplied by Magic Valley Laboratories and were triple-rinsed with the water being sampled. All samples were labeled and stored on ice until delivered to Magic Valley Laboratories' receiving center in Pocatello at the end of the day. Samples were analyzed using the following standard methods: dissolved sodium, Method SM3111B; dissolved potassium, Method SM3111B; dissolved magnesium, Method SMB3111B; dissolved calcium, Method SM3111D; fluoride, Method EPA300.0; chloride, Method EPA300.0; nitrate-N, Method EPA300.0; sulfate, Method EPA300.0; carbonate, Method SM2320B; bicarbonate, Method SM2320B; ammonia, Method EPA350.1; total organic nitrogen (Kjeldahl), Method PA1-DK03. Bromide was analyzed by a non-standard, ion-chromatographic method.

Field sampling notes, including sampling dates, sample numbers and corresponding site numbers, are summarized in A.1. Water level measurement information is summarized in A.2.

A.1. Field Sampling Notes

Sample Number	Date (yymmdd)	Site Number	Sampling Notes
001	060921	041	Sample was collected from the end of a running linear next to Rast Road. Two wells appear to be connected
002	060928	039	12:01 from faucet by well
003	060928	038	10:22 pump ran at least 10 minutes; sample was digested by lab
004	060929	016	8:46 5 minute flush; well pumps sand
005	060928	040	9:24 from spigot south of pump
006	060928	039	9:40 from runing pump
007	060928	036	11:18 from runing pump
008	060928	037	10:35 from runing pump; digested by lab
009	060929	031	9:32 from spigot by well, 4 minute flush
010	060928	035	11:20 surface grab sample from canal
011	060929	018	8:51 from faucet near well in cellar; flushed 30 seconds
012	060929	030	8:58 from end of rain bird
013	060929	032	9:20 from running pump; digested by lab
014	060929	033	9:03 from hydrant 30 m east of well; flushed 3 minutes
015	060929	016	10:12 from hydrant 20 m east of well; flushed 4 minutes; turbid, digested by lab
016	060929	029	10:18 Joe Meyer new well, from hydrant by wind mill; digested by lab
017	061012	028	9:03 canal, east end of Lamb-Weston area; flow velocity ca. 10cm/s
018	061012	027	9:47 Carlson well on Whitnah Road, faucet by well; flushed 1 minute
019	061012	042	canal at Whitnah road, by gate M66; flow velocity ca. 2cm/s
020	061012	026	10:00 Wada Farms well, from hydrant

Sample Number	Date (yyymmdd)	Site Number	by shop; from spigot 30 yd. from well Sampling Notes
021	061012	003	10:15 Roger Whitnah well, from hydrant by corral, ca. 30 yd. from well
022	061012	025	10:31 France well
023	061012	024	10:43 canal across Whitnah Road from France well; velocity ca. 12cm/s
024	061012	023	10:57 sample from R lateral canal spillway; flow velocity ca. 3 L/s
025	061012	022	11:15 Gary Simms well; ca. 200 ft deep according to wife Diane
026	061012	021	11:45 Kenneth Simms (Agnes) well, from hydrant by well; water was tested 10 years ago; taste usually goes awry in July/August and is worst ca. two weeks after canal stops flowing; local soil is sandy
027	061012	020	12:15 from canal at S lateral gate on highway; duplicate to 028
028	061012	012	15:49 duplicate to 027
029	061012	019	12:28 Cruz well
030	061012	02	12:15 Barret (?) well
031	061012	011	16:05 Klausen well, duplicate to 032
032	061012	011	16:05 duplicate to 031
033	061012	010	Canal ca. 50 yd. from Klausen well
034	061012	009	16:48 canal across from Dave Bethke well
035	061025	008	9:30 Dr. Dell Rudd, house faucet near well
036	061025	007	10:16 natural seep 5 m below Reservoir's high water mark; ca. 1 gpm flow
037	061025	006	10:58 Knudsen well
038	061025	005	11:30 Ron Mauch well, ca. 200 ft west of Knudsen well; TD = 180 ft bls, pump at 140 ft bls
039	061025	004	11:50 Spring Hollow spring; canal is dry, so no dilution; no visible spring flow but estuary pool is clear and actively stirred by inflow; soils in vicinity are fine sand

Sample Number	Date (yyymmdd)	Site Number	Sampling Notes
040	061025	013	13:00 Doug Whitnah well, ca. 50 ft from canal; well is unused, murky; collected two thief samples 10 feet off bottom, midway in water column; sample needs to be filtered
041	061025	002	15:10 Poulson deep well; flushed 2 minutes; need high-pressure gage to measure swl
042	061025	001	15:15 Poulson shallow well; ca. 50 yd. west of deep well, in concrete pit below frost line
043	061114	003	10:32 Roger Whitnah well
044	061114	026	10:47 Wada Farms well
045	061114	021	10:52 Kenneth Simms (Agnes) well
046	061114	004	11:10 Spring Hollow, after a runoff event; from scour marks, canal appears to have flowed considerably in response to the rainfall event; estuary level is ca. 6" higher than October 25
047	061114	014	11:20 Bethke deep well
048	061114	018	11:47 Gohl domestic well; TD = 365 ft; flushing test; sampled after 30 second flush;
049	061114	018	11:50 after 3 minute flush
050	061114	018	12:00 after 10 minute flush
051	061114	018	12:15 after 10 minute flush (duplicate)
052	061114	029	13:59 from hydrant 100 m north of well (by windmill); flushed 15 seconds
053	061114	029	13:59 Joe Meyer well; flushed 10 minutes
054	061114	034	14:10 Joe Meyer new well; from kitchen sink
055	061119	004	18:00 Spring Hollow
056	061225	003	Roger Whitnah well; flushed 10 seconds
057	061225	026	Wada Farms well; no flush to avoid mess
058	061225	021	Agnes Simms well; flushed 10 seconds
059	061225	018	Gohl domestic well; hydrant frozen; sampled from tank faucet

060 Sample Number	061225 Date (yyymmdd)	014 Site Number	Bethke deep well Sampling Notes
061	061226	014	Duplicate to 060 collected the next morning
062	061225	004	Two dozen ducks in the estuary
063			Unused sample number
064	070322	004	Spring Hollow; split sample with 065 for N-isotope analysis
065	070322	004	Spring Hollow
066	070413	011	7:13 Klausen well
067	070413	004	7:22 Spring Hollow
068	070413	018	9:16 Gohl domestic well
069	070413	014	9:05 Bethke deep well
070	070413	004	7:22 Spring Hollow
071	070413	003	11:18 Roger Whitnah well
072	070413	021	9:27 Agnes Simms well
073	070413	026	9:39 Wada Farms well
074	070413	003	11:18 Roger Whitnah well
075	070521	045	8:40 Povey well; from faucet by pump
076	070521	054	8:50 Rowe well on Povey Road; from faucet by well
077	070521	033	9:12 Maria Rast irrigation well NE; from end of wheel line
078	070521	037	9:21 Gehring North well; sampled for N-isotopes only
079	070521	046	9:33 Tiede well in shed; sampled from faucet
080	070521	099	10:30 Tiede well, east of Russet Road and west of Tiede shed; sampled from faucet
081	070521	032	11:05 Tiede well by Visiting Road; sampled from faucet
082	070521	052	11:20 Tiede well N of Rast Road sampled from faucet by pump

Sample Number	Date (yyymmdd)	Site Number	Sampling Notes
083	070521	000	11:30 Maria Rast irrigation well SW; sampled from end of wheel line
084	070521	035	11:55 Gohl irrigation well west; sampled from end of wheel line
085	070521	030	11:40 Maria Rast irrigation well SE sampled at beginning of wheel line
086	070521	035	12:10 Gohl irrigation well west; sampled from faucet by pump
087	070521	036	12:17 Gohl irrigation well west
088	070521	004	12:55 Spring Hollow; sampled 20 m downstream in estuary, so sample is a mixture of spring and canal water
089	070521	054	13:20 Rowe well on Povey Road; sampled from faucet by pump
090	070521	004	14:30 Spring Hollow; some dilution by canal flow
091	070523	047	10:30 Tiede well on Russet Road
092	070523	003	10:55 R Whitnah hydrant by corral
093	070523	026	11:05 from hydrant by shop
094	070523	021	11:35 Agnes Simms well; from hydrant on well pit
095	070523	019	11:50 Cruz well; hydrant east of well pit
096	070523	033	12:10 Maria Rast well; hydrant east of well house
097	070523	034	13:05 Joe Meyer well, sampled from kitchen sink
098	070523	029	13:30 Joe Meyer well, hydrant by windmill; flushed 5 minutes
099	070523	012	13:50 D Whitnah (Barrett) well
100	070523	006	14:00 Knudsen well
101	070523	008	15:00 Rudd well
102	070523	002	19:30 Poulson deep, from faucet by pump; two 1-minute runs @ 2.7 kW demand

Sample Number	Date (yymmdd)	Site Number	Sampling Notes
103	070523	001	19:35 Poulson shallow well, from hydrant east of house
104	070524	014	9:34 Bethke deep well
105	070524	011	9:41 Klassen well; faucet in cellar by well
106	070524	011	9:42 Klassen well; faucet in cellar by well
107	070605	037	20:22 Gehring N well, from faucet by pump before heavy rain

A.2. Water Well and Water Level Datum Records

Site	Well Name	Well Permit	Sample Type	Sampling Notes	Measuring Point (meters relative to land surface)
1	Poulson Shallow	010001	well dom	well located in pit below frost line	-1.62
2	Poulson Deep	710344	well	well located at NW corner of shop building	
3	R Whitnah	010003	well dom	well depth is 60.0 ft	1.28
4	Spring Hollow		spring		
5	Ron Mauch		well dom		0.69
6	Knudsen well	710255	well dom	too many wires	0.30
7	Knudsen seep		spring	seep debouches at a point that is 3-5 ft lower than two years ago	
8	Rudd	800581	well dom		0.93
9	Canal Rast		canal		
10	Canal Center PVR		canal		
11	Klassen	814523	well dom		0.38
12	D Whitnah Deep	781783	well dom		
13	D Whitnah shallow		well dom	Located in shed; well depth 94.0 ft	-0.48
14	Bethke Deep	778243	well dom	small access hole	
15	Bethke Shallow		well dom	needs 1 1/4" cap	-0.64
16	Gohl dom old		well dom	chronically pumps sand	
17	ASCC suppl.	816342	well irr	water surface has oil on it	
18	Gohl dom new	827142	well dom	8 inch casing 365 ft deep	0.55
19	Cruz		well dom	well located near canal	
20	Canal South PVR		canal		
21	Agnes Simms		well dom		
22	Gary Simms		well dom		
23	R lat South PVR		canal		
24	S Lat Canal Whitnah		canal		
25	Dan France		well dom		0.06
26	Wada-Polzin	800563	well dom		
27	Carlson		well dom		
28	S lat Lamb		canal		
29	Joe Meyer new	794411	well dom		
30	Maria Rast irrig 4		well irrig	distribution system is located near the house	
31	adolf new		well dom	hydrant is by the casing, with cap	
32	Tiede 13 west	710668	well irr		4.8
33	Maria Rast dom	800575	well dom		
34	Joe Meyer old		well dom	East side of windmill, concrete lid	
35	Gohl irrig W	794412	well irr		
36	Gohl irrig E	794410	well irr	Gohl irrigation east well	4.0
37	Gehring 17 N	800576	well irr		
38	Gehring 17 S	800574	well irr	Ring lock on inspection port at 0.7m; chem valve at 1.1 m above ground	0.70

Site	Well Name	Well Permit	Sample Type	Sampling Notes	Measuring Point (meters relative to land surface)
39	Gehring near Breeding's well	827083	well irr	no tape port; 3/4" faucet at 1.2m; chem valve at 1.7m above ground	1.2
40	Near Tony Burgem	800608	well irr	Lance Funk, operator	1.1
41	Well on linear sprinkler		well irr	Kim Wahlen operator; tape port has ring lock port at 1.10m; chem valve at 1.60m	
42	Main canal at Whitnah	canal			
44	Friesen		well dom	one piece cap difficult to remove	0.5
45	Povey		well irr	pumptop at 1.77m; air vent at 1.30m; chem valve at 1.24m above ground	1.3
46	Tiede in Sec.18		well irr	metal roof; ring lock inspection port at 0.45m; chem valve at 0.93m above ground.	0.45
47	Tiede	710667	well irr	tape port=3/4"; faucet at 9.64m; chem valve at 10.10m	9.64
48	Bethke near Adolf	710772	well irr	Well tag # D0004046; nice tape port, 3/4"; faucet at 1.4m; chem valve at 2.0m has 1 1/4" port	1.4
49	Funk in 17		well irr		
50	Gehring 18 NE		well irr		
51	Gehring 18 SE		well irr	3/4" faucet at 2.0m; chem valve at 2.60m above ground	2.0
52	Tiede on Rast's		well irr		0.5
53	Adolf (old well)		well dom	well bore is crooked; no tape or echo sounding possible	
54	Rowe on Povey's		well irr		0.8
55	Breeding Rast Pump		well irrig		
56	Lance Funk		well dom		
57	Tony Burgemeister		well dom	well located in pit; no measurement access	
58	Jeffries		well dom	Michaelson drilled the well behind the house; cap has rusty bolts	

Table 1. Static water level measurements made during this study. "Tape" refers to electrical conductance measurement; "Sonic" to the ultrasonic time-of-travel method.

Site #	Elevation (ft, amsl)		
	Date	Tape	Sonic
41	01/14/07		1305.19
41	03/31/07		1305.9
41	03/31/07		1305.93
41	03/31/07		1305.93
41	04/26/07		1306.52
41	04/26/07	1306.58	
32	01/11/07		1304.58
32	01/14/07		1304.58
32	04/02/07		1305.11
32	04/26/07		1305.68
39	01/14/07		1308.21
39	04/02/07		1308.78
36	01/11/07		1318.14
36	03/31/07		1319.12
11	10/12/06	1323.04	
11	04/14/07	1324.21	
11	04/14/07	1324.40	
11	04/25/07	1324.25	
11	04/13/07	1325.34	
3	12/25/06	1330.88	
3	12/25/06	1328.11	
3	04/14/07	1325.72	
14	10/12/06	1316.63	
14	01/10/07	1319.51	1319.48
14	04/14/07		1319.81
18	10/12/06	1317.45	
18	11/14/06	1319.34	
18	04/14/07		1319.93
6	10/25/06	1320.93	
8	04/02/07		1315.07
2	04/26/07	1325.30	1325.56
2	04/26/07	1325.90	
2	04/26/07	1325.92	
2	04/26/07		1325.56
1	10/25/06	1332.02	
1	04/25/07	1330.33	1330.2
1	04/25/07		1330.31
1	04/25/07	1330.34	

Table 2. Duplicate samples collected for quality assurance evaluation of water quality data.

Site #	Sample #	Date	Na	K	Mg	Ca	F	Cl	Br	NO3-N	SO4	CO3	HCO3	Comment
39	2	28-Sep-06	22.5	3.7	19.7	49.6	0.5	38.4	0.05	1.23	52.3	<1	204	12:01 corrected site no from 34 to 39
39	6	28-Sep-06	22	3.7	19.8	48.4		37	<0.05	1.21	50.9	<1	164	9:40 pump running
16	4	29-Sep-06	25.5	4.4	23.2	51.5		65.5	0.09	0.53	75.3	<1	142	8:46 run 5 minutes
16	15	29-Sep-06	26.1	4.5	21.6	49.2		61.2	0.08	0.51	67.2	<1	141	10:12 run 4 minutes. turbid. digested by lab
11	31	12-Oct-06	13	2.8	11.5	39.6		12.2	<0.05	0.42	26.1	<1	168	16:05
11	32	12-Oct-06	12.9	2.7	11.7	40.4		11.7	<0.05	0.38	26.1	<1	167	16:05
18	48	14-Nov-06	31.2	4.8	24.8	68.6		80.2	0.13	1.8	75.9	<1	167	11:47 30 sec
18	49	14-Nov-06	30.6	4.6	25.1	66.4		78.8	0.12	1.86	73.9	<1	171	11:50 3 min
18	50	14-Nov-06	31	4.6	24.9	67.8		80.7	0.14	1.88	76.2	<1	174	12:00 10 min prerun test with 048 049 and 051
18	51	14-Nov-06	31.2	4.7	25.4	68.1		80.8	<0.05	1.92	76.8	<1	174	12:15 10 min duplicate
14	60	25-Dec-06	38.8	5.1	21.7	65.4	0.43	75.3		2.61	82.7	<1	182	
14	61	26-Dec-06	36.9	4.5	22.6	62.4	0.33	73		2.38	80.6	<1	172	duplicate taken next morning
4	67	13-Apr-07	90.6	12	62.9	93.2	0.49	91.5		40.7	205	<1	240	
4	70	13-Apr-07	87.2	11	61.9	92.9	0.48	89.8		40.3	203	<1	241	
35	84	21-May-07	34.4	5.2	19.3	50.9	0.46	55.5		1.6	67.2	<1	180	11:55 Gohl irr west; end of wheel line
35	86	21-May-07	34.2	5.2	18.9	51.4	0.49	47.5		1.63	64.1	<1	168	12:10 Gohl irr west; beets; faucet by pump
11	105	24-May-07	13.8	3.3	14.6	52.7	0.56	27.2		1.14	37.5	<1	170	9:41 Klassen; faucet in cellar by well
11	106	24-May-07	13.7	3.3	14.9	51.5	0.56	26.6		1.13	36.5	<1	152	942 Klassen; faucet in cellar by well

Table 3. All water quality sampling results organized by site number and sampling date.

Site	Name	Sample	Date	Na	K	Mg	Ca	Cl	F	Br	NO ₃ -N	SO ₄	CO ₃	HCO ₃	Charge Balance, %
1		42	10/25/2006	35.2	9.1	29.0	56.5	24.6		<0.05	7.15	112	<1	209	3.0
1		103	05/23/2007	34.7	9.9	29.0	65.5	26.9	0.46		9	99.1	<1	234	4.1
2		41	10/25/2006	43.7	5.4	23.9	56.1	47.0		0.05	1.25	120	<1	194	-1.6
2		102	05/23/2007	42.2	5.8	25.1	61.0	50.4	0.48		0.96	117	<1	200	-0.6
3		21	10/12/2006	22.8	7.7	27.0	70.3	18.7	0.64	<0.05	6.84	58.3	<1	272	4.3
3		43	11/14/2006	25.1	8.8	30.5	81.7	22.8		<0.05	9.95	67.4	<1	269	8.8
3		56	12/25/2006	38.8	9.5	44.0	120.0	62.3	0.53		25.4	178	<1	274	5.2
3		71	04/13/2007	55.2	9.4	46.4	124.0	78.2	0.48		30.5	230	<1	238	5.1
3		74	04/13/2007	64.2	9.6	52.9	137.0	80.4	0.48		31.5	235	<1	220	11.5
3		92	05/23/2007	33.9	9.3	37.5	93.6	54.2	0.48		26.2	105	<1	248	7.0
4	Spring Hollow	39	10/25/2006	82.4	11.0	57.3	85.9	81.9		0.07	36.3	195	<1	248	7.7
4	Spring Hollow	46	11/14/2006	85.8	11.0	57.6	91.0	85.8		0.11	37.8	199	<1	248	8.4
4	Spring Hollow	55	11/19/2006	81.5	10.8	55.4	84.4	86.6		0.13	38.4	202	<1	222	7.2
4	Spring Hollow	62	12/25/2006	85.4	12.0	56.1	90.9	93.5	0.52		40.3	219	<1	250	4.8
4	Spring Hollow	65	03/22/2007	85.4	11.0	62.1	100.0	87.3	0.50		40.6	216	<1	240	9.8
4	Spring Hollow	70	04/13/2007	87.2	11.0	61.9	92.9	89.8	0.48		40.3	203	<1	241	9.6
4	Spring Hollow	67	04/13/2007	90.6	12.0	62.9	93.2	91.5	0.49		40.7	205	<1	240	10.2
4	Spring Hollow	88	05/21/2007	22.5	3.8	18.4	47.7	28.1	0.53		5.89	71.2	<1	149	1.3
5		38	10/25/2006	33.1	4.5	22.4	50.3	53.8		0.08	1.42	66.3	<1	190	-1.1
6		37	10/25/2006	42.2	4.5	21.1	52.5	56.5		<0.05	2.54	75.6	<1	184	0.6
6		100	05/23/2007	39.3	4.9	19.8	60.1	59.9	0.43		2.73	79.7	<1	203	-2.1
7	Knudsen seep	36	10/25/2006	51.9	8.6	32.4	58.0	42.0		<0.05	6.27	92.4	<1	262	3.4
8		35	10/25/2006	42.0	4.6	21.3	51.1	53.2		0.08	2.56	74.4	<1	186	0.8
8		101	05/23/2007	37.5	4.7	21.2	59.4	54.0	0.44		2.38	76.4	<1	188	1.6
9	Canal Rast	34	10/12/2006	11.9	2.4	10.2	34.9	11.4		<0.05	<0.03	27.6	32	104	-7.5
10	Canal Center	33	10/12/2006	11.8	2.3	9.8	34.9	10.6	0.83	<0.05	<0.03	27.2	32	104	-8.3
11		32	10/12/2006	12.9	2.7	11.7	40.4	11.7		<0.05	0.38	26.1	<1	167	-0.1
11		31	10/12/2006	13.0	2.8	11.5	39.6	12.2		<0.05	0.42	26.1	<1	168	-1.2
11		66	04/13/2007	18.5	3.5	17.6	51.5	15.0	0.63		3	42.7	<1	169	8.2
11		106	05/24/2007	13.7	3.3	14.9	51.5	26.6	0.56		1.13	36.5	<1	152	5.0
11		105	05/24/2007	13.8	3.3	14.6	52.7	27.2	0.56		1.14	37.5	<1	170	1.5
12		28	10/12/2006	37.2	4.9	22.9	56.7	22.7		<0.05	4.84	58.8	<1	219	7.7
12		99	05/23/2007	35.4	5.3	21.6	59.4	32.1	0.38		5.94	72.2	<1	223	1.9
13		40	10/25/2006	15.3	6.2	13.3	27.3	14.1		<0.05	0.47	39.4	<1	122	0.8
14		47	11/14/2006	41.1	4.8	23.8	64.9	74.2		0.12	2.44	78.9	<1	189	1.7
14		60	12/25/2006	38.8	5.1	21.7	65.4	75.3	0.43		2.61	82.7	<1	182	-0.2
14		61	12/26/2006	36.9	4.5	22.6	62.4	73.0	0.33		2.38	80.6	<1	172	0.6
14		69	04/13/2007	38.1	4.3	23.3	62.1	70.8	0.41		2.64	75.3	<1	172	2.5
14		104	05/24/2007	39.5	5.2	24.6	68.6	84.5	0.38		2.73	87.2	<1	173	1.4
16		15	09/29/2006	26.1	4.5	21.6	49.2	61.2		0.08	0.51	67.2	<1	141	0.3
16		4	09/29/2006	25.5	4.4	23.2	51.5	65.5		0.09	0.53	75.3	<1	142	-0.5

Table 3 (cont'd). All water quality sampling results organized by site number and sampling date.

Site	Name	Sample	Date	Na	K	Mg	Ca	Cl	F	Br	NO ₃ -N	SO ₄	CO ₃	HCO ₃	Charge Balance, %
18		11	09/29/2006	31.3	5.1	25.3	66.0	83.8		0.10	1.88	78.7	<1	180	-0.9
18		49	11/14/2006	30.6	4.6	25.1	66.4	78.8		0.12	1.86	73.9	<1	171	1.7
18		51	11/14/2006	31.2	4.7	25.4	68.1	80.8		<0.05	1.92	76.8	<1	174	1.5
18		50	11/14/2006	31.0	4.6	24.9	67.8	80.7		0.14	1.88	76.2	<1	174	1.1
18		48	11/14/2006	31.2	4.8	24.8	68.6	80.2		0.13	1.8	75.9	<1	167	2.5
18		59	12/25/2006	28.5	4.9	21.1	63.3	79.3	0.42		1.82	75.5	<1	166	-2.5
18		68	04/13/2007	29.4	4.9	26.1	61.3	75.4	0.38		1.7	70.5	<1	167	1.8
19		29	10/12/2006	14.8	4.4	16.5	47.6	16.7		<0.05	3.36	41.4	<1	174	2.8
19		95	05/23/2007	16.0	5.7	18.9	46.1	23.2	0.62		2.08	51.1	<1	173	0.8
20	Canal South	30	10/12/2006	11.9	2.4	10.1	33.8	12.5		<0.05	<0.03	28.5	26	97	-4.7
20	Canal South	27	10/12/2006	11.3	2.0	10.3	33.6	11.4	0.91	<0.05	<0.03	27.7	20	106	-4.4
21		26	10/12/2006	22.4	6.3	20.6	42.0	14.2	0.71	<0.05	7.22	46.7	<1	163	8.0
21		45	11/14/2006	24.7	7.0	22.4	44.7	14.1		<0.05	8.1	49	<1	170	10.3
21		58	12/25/2006	22.6	6.9	22.3	41.4	14.9	0.69		7.74	49.6	<1	174	6.2
21		72	04/13/2007	23.3	1.2	24.0	47.1	19.5	0.65		5.18	49.6	<1	184	6.5
21		94	05/23/2007	20.3	8.2	28.1	46.1	13.8	0.60		3.88	57.8	<1	237	1.2
22		25	10/12/2006	36.0	4.4	17.6	45.0	35.2		<0.05	1.38	59	<1	143	7.9
23	R lat South	24	10/12/2006	12.0	2.5	9.8	34.5	12.5		<0.05	<0.03	27.5	16	114	-3.3
24	S Lat Canal	23	10/12/2006	11.9	2.3	9.6	34.2	12.8	0.92	<0.05	<0.03	28.9	16	110	-4.3
25		22	10/12/2006	42.1	6.9	17.9	49.9	14.1		<0.05	<0.03	69.9	<1	249	0.3
26		20	10/12/2006	19.9	3.6	17.9	53.9	41.5		<0.05	0.78	63.3	<1	150	1.6
26		44	11/14/2006	21.6	3.8	18.8	52.9	39.5		0.07	0.68	60.6	<1	148	4.1
26		57	12/25/2006	20.7	3.8	19.1	52.3	41.4	0.42		0.79	63.9	<1	148	2.2
26		73	04/13/2007	21.4	3.7	20.3	56.7	40.3	0.44		0.85	58	<1	144	7.6
26		93	05/23/2007	20.5	4.1	19.5	55.7	48.6	0.44		0.84	69	<1	147	1.2
27		18	10/12/2006	30.1	4.6	18.5	51.6	49.1		0.06	1.48	32.2	<1	178	5.0
28	S lat Lamb	17	10/12/2006	12.5	2.4	9.5	35.5	12.0	0.93	<0.05	<0.03	26.8	6	124	-0.3
29		16	09/29/2006	71.4	7.0	69.4	196.0	345.0		0.49	6.96	245	<1	175	2.6
29		53	11/14/2006	124.0	7.2	91.8	178.0	466.0		0.65	12.4	340	<1	194	-3.5
29		52	11/14/2006	60.6	6.6	71.4	167.0	466.0	0.34	0.76	10.4	236	<1	307	-15.6
29		98	05/23/2007	101.0	8.1	81.6	203.0	459.0	0.28		12.5	251	<1	188	-0.1
30		12	09/29/2006	54.0	6.2	40.3	76.6	188.0		0.3	4.8	140	<1	167	-6.7
30		85	05/21/2007	52.2	6.2	40.1	54.9	187.0			5.2	125	<1	183	-12.9
31		9	09/29/2006	32.7	4.4	23.6	58.2	63.0		0.09	1.88	72.8	<1	187	-0.1
32		13	09/29/2006	37.3	4.4	24.9	63.7	70.6		0.10	2.02	77.6	<1	187	1.9
33		14	09/29/2006	42.7	5.1	23.7	66.4	77.9		0.10	2.6	86.7	<1	172	2.7
33		77	05/21/2007	46.5	5.0	27.1	67.7	91.7	0.39		3.47	92.6	<1	209	-1.7
33		96	05/23/2007	42.8	5.3	24.8	66.8	101.0	0.41		2.84	94.6	<1	184	-3.5
34		54	11/14/2006	62.6	7.3	73.8	185.0	383.0		0.63	6.55	218	<1	177	-0.4
34		97	05/23/2007	66.6	7.9	78.2	208.0	406.0	0.33		11.1	218	<1	167	2.5
35		10	09/28/2006	36.0	5.1	18.8	51.0	43.6		0.06	1.48	63.6	<1	167	4.2

Table 3 (concluded). All water quality sampling results organized by site number and sampling date.

Site	Name	Sample	Date	Na	K	Mg	Ca	Cl	F	Br	NO ₃ -N	SO ₄	CO ₃	HCO ₃	Charge Balance, %
35		86	05/21/2007	34.2	5.2	18.9	51.4	47.5	0.49		1.63	64.1	<1	168	2.3
35		84	05/21/2007	34.4	5.2	19.3	50.9	55.5	0.46		1.6	67.2	<1	180	-1.8
36		7	09/28/2006	33.3	5.3	19.4	46.2	35.9		<0.05	1.14	58.2	<1	179	2.9
36		87	05/21/2007	33.4	5.4	18.5	48.0	39.2	0.50		1.25	59.4	<1	171	2.9
37		8	09/28/2006	43.1	4.5	26.8	64.7	80.2		0.11	2.47	87.2	<1	172	3.4
38		3	09/28/2006	44.1	4.7	27.1	65.1	81.2	0.32	0.11	2.82	88.9	<1	188	1.5
39		6	09/28/2006	22.0	3.7	19.8	48.4	37.0		<0.05	1.21	50.9	<1	164	2.9
39		2	09/28/2006	22.5	3.7	19.7	49.6	38.4	0.50	0.05	1.23	52.3	<1	204	-3.7
40		5	09/28/2006	21.4	3.6	18.3	43.8	34.5		<0.05	1.17	44.2	<1	157	2.5
41	linear	1	09/21/2006	21.5	3.5	18.0	46.4	37.7	0.54		1.19	45.7	<1	144	4.3
42	Main canal	19	10/12/2006	11.3	2.6	9.9	34.5	11.4	0.92	<0.05	<0.03	26.1	<1	134	-0.3
45		75	05/21/2007	68.4	6.3	42.6	125.0	208.0	0.32		8.45	153	<1	185	2.5
54		76	05/21/2007	57.0	5.7	32.4	84.5	121.0	0.37		4.59	124	<1	203	0.5
54		89	05/21/2007	57.0	5.6	32.3	81.2	117.0	0.41		4.6	142	<1	187	-0.5

Average Charge Balance : 2.0 %

RMS Charge Balance error: 3.7%

Table 4. Summary of all stable isotope data collected, sorted by sample site.

SITE #	SAMPLE #	DATE	$\delta^{18}\text{O}$	$\delta^2\text{H}$	$\text{NO}_3\text{-N}$	NH_4	Total Org-N	$\delta^{15}\text{N}$
1	42	10/25/2006	-16.8	-128	7.2			
1	103	5/23/2007	-16.73	-128	9	<0.05	0.33	5.08
2	41	10/25/2006	-17.4	-134	1.3			
2	102	5/23/2007	-17.66	-134	1	<0.05	0.22	6.27
3	21	10/12/2006	-16.7	-129	6.8			
3	43	11/14/2006	-16.6	-127	10			
3	56	12/25/2006	-16	-126	25.4			
3	71	4/13/2007	-15.92	-125	30.5			
3	92	5/23/2007	-16.57	-127	26.2	<0.05	0.31	7.53
4	39	10/25/2006	-15.9	-125	36.3			
4	46	11/14/2006	-15.9	-125	37.8			
4	55	11/19/2006	-15.7	-124	38.4			
4	65	3/22/2007	-15.89	-125	40.6	<0.05	<0.05	2.65
4	67	4/13/2007	-15.57	-124	40.7			
5	38	10/25/2006	-17.7	-136	1.4			
6	37	10/25/2006	-17.6	-134	2.5			
6	100	5/23/2007			2.7	<0.05	0.34	5.43
8	35	10/25/2006	-17.6	-134	2.56			
8	101	5/23/2007			2.4	<0.05	<0.05	5.42
9	34	10/12/2006	-16.9	-130	0			
10	33	10/12/2006	-14.5	-124	0			
12	28	10/12/2006	-16.9	-130	4.8			
12	99	5/23/2007			5.9	<0.05	0.2	3.58
13	40	10/25/2006	-16.6	-128	0.5			
14	47	11/14/2006	-17.5	-133	2.4			
18	59	12/25/2006	-17.78	-136	1.8			
18	68	4/13/2007	-17.79	-136	1.7			
19	95	5/23/2007			2.1	<0.05	0.19	4.72
20	27	10/12/2006	-16.9	-130	0			
21	26	10/12/2006	-16.9	-127	7.2			
21	45	11/14/2006	-16.8	-130	8.1			
21	58	12/25/2006	-16.8	-129	7.7			
21	72	4/13/2007	-16.8	-128	5.18			
21	94	5/23/2007	-16.79	-128	3.88	<0.05	0.32	5.21
22	25	10/12/2006	-17.8	-135	1.38			
23	24	10/12/2006	-16.9	-129	0			
26	20	10/12/2006	-18.2	-138	0.8			
26	57	12/25/2006	-18.19	-137	0.8			
26	73	4/13/2007	-18.16	-137	0.85			
28	17	10/12/2006	-17	-128	0			
29	98	5/23/2007	-16.9	-130	12.5	<0.05	0.32	5.05
33	96	5/23/2007	-17.61	-134	2.8	<0.05	0.25	5.28
34	97	5/23/2007	-17.08	-131	11.1	<0.05	0.26	6.64
37	8	9/28/2006			2.5			5.06
42	19	10/12/2006	-16.9	-129	0			

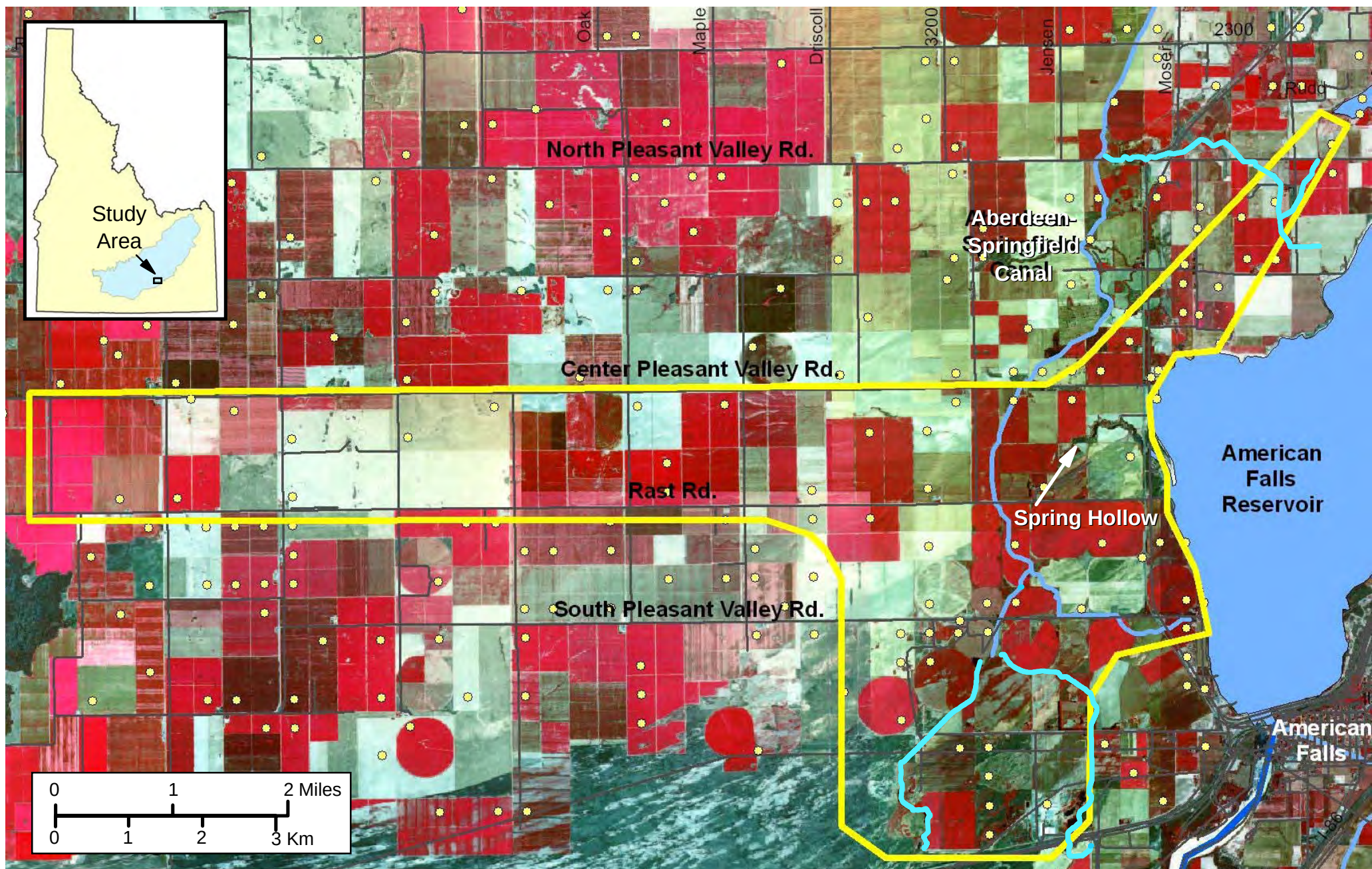
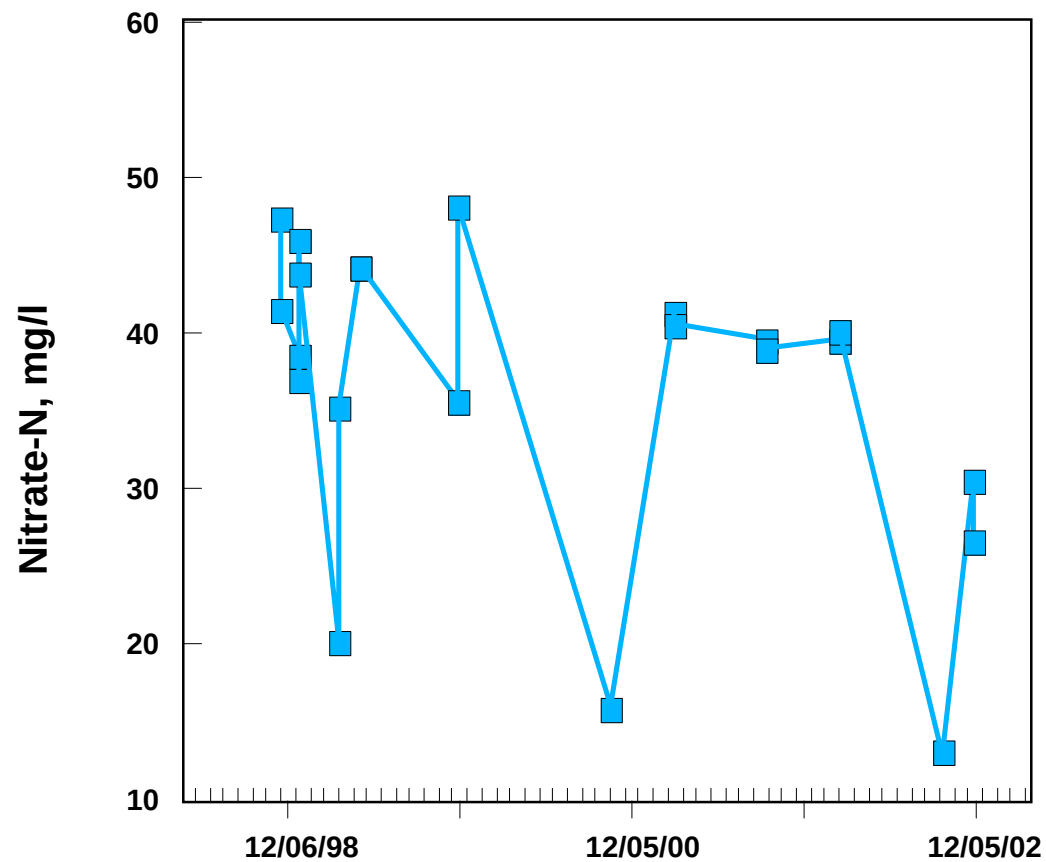


Figure 1. Study area showing extent of irrigated land, principal hydrographic features, and approximate extent of the sampled area (yellow boundary). The natural seep at Spring Hollow is located at the western edge of its estuary.



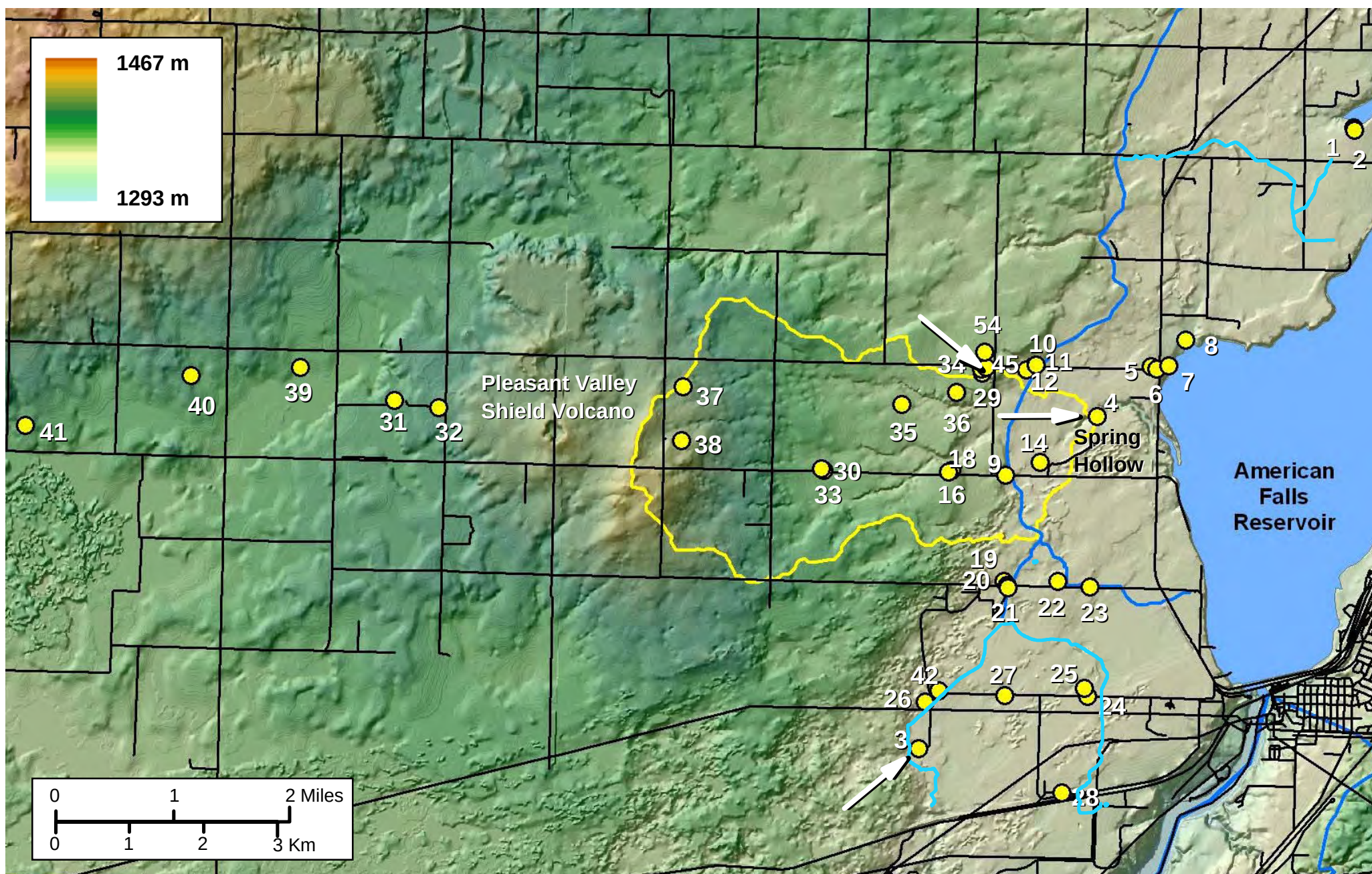


Figure 3. Location of sampling sites, showing site numbers. Polygon indicates approximate geographic extent of the watershed that may support Spring Hollow's perennial flow. Aberdeen-Springfield canal system is shown in blue. Arrows highlight sampling locations of interest.

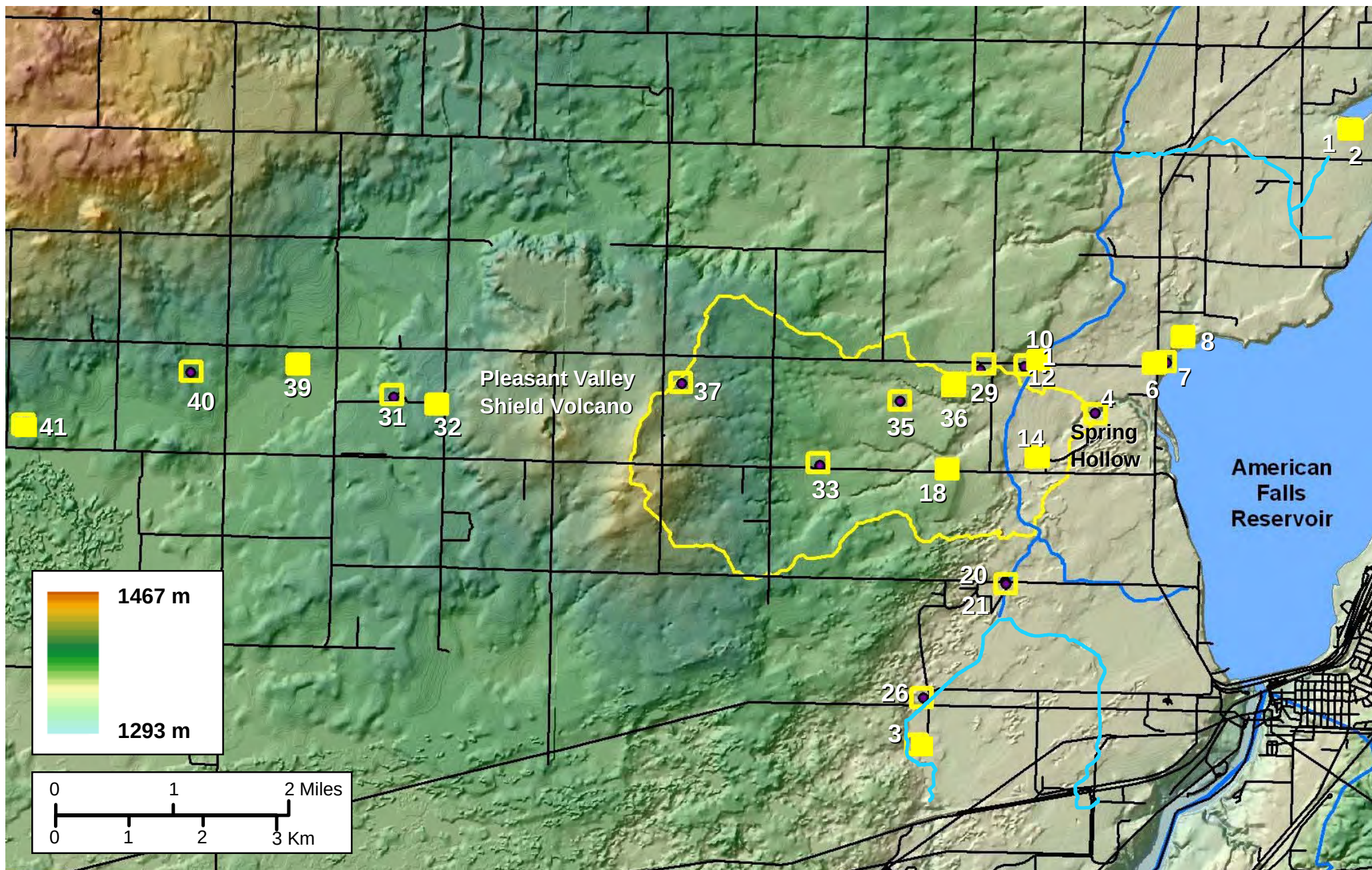


Figure 4. Locations where drillers' logs were available, showing sampling site numbers. Filled rectangles are locations of water-level measurements.

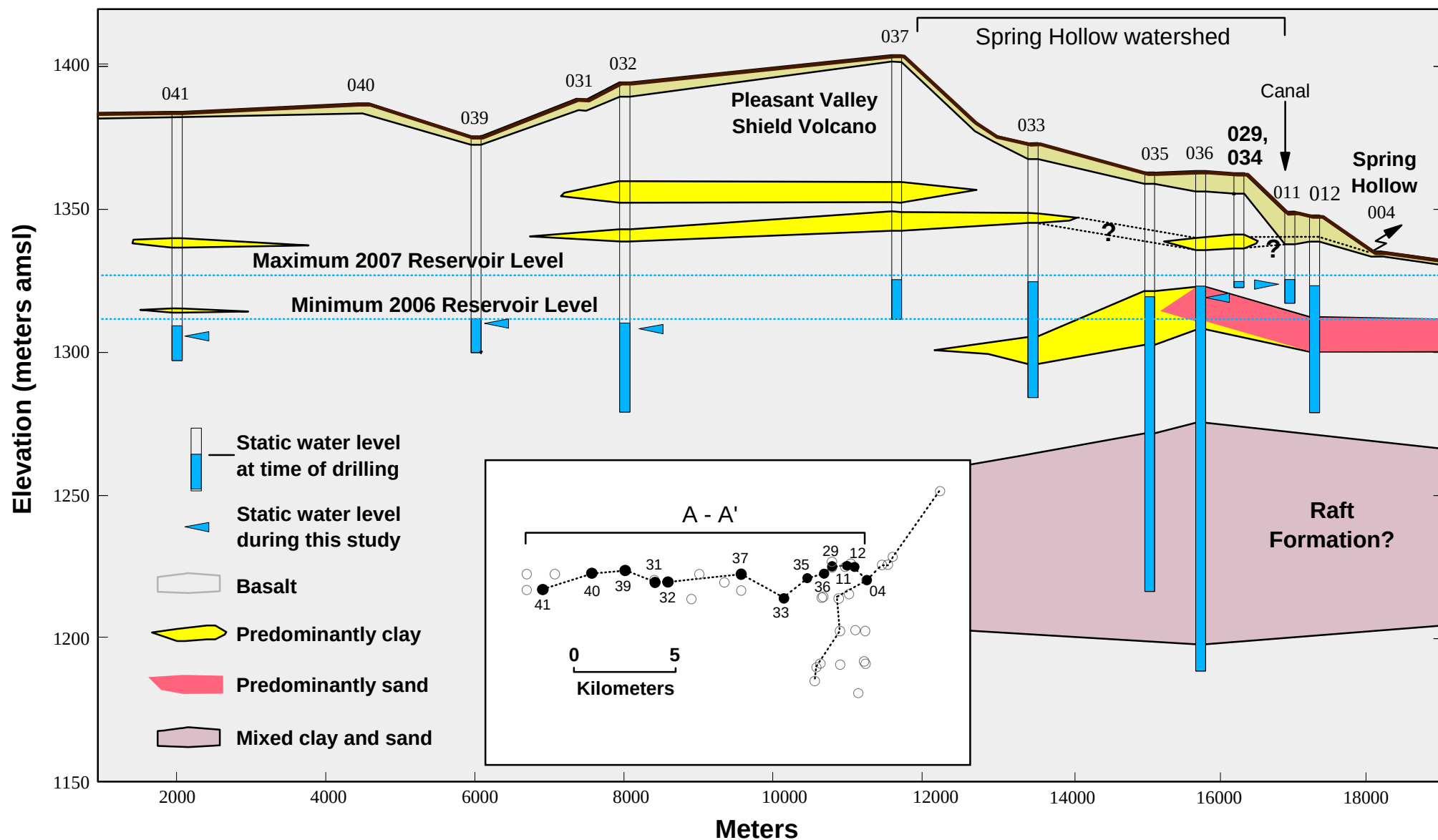


Figure 5a. Subsurface stratigraphy of the study area based on drillers' logs along section A-A'. Water levels at time of drilling are shown as blue bars; blue arrowheads indicate water levels measured during this study. Horizontal dashed lines represent range of water surface elevations in American Falls Reservoir between August, 2006 and April, 2007.

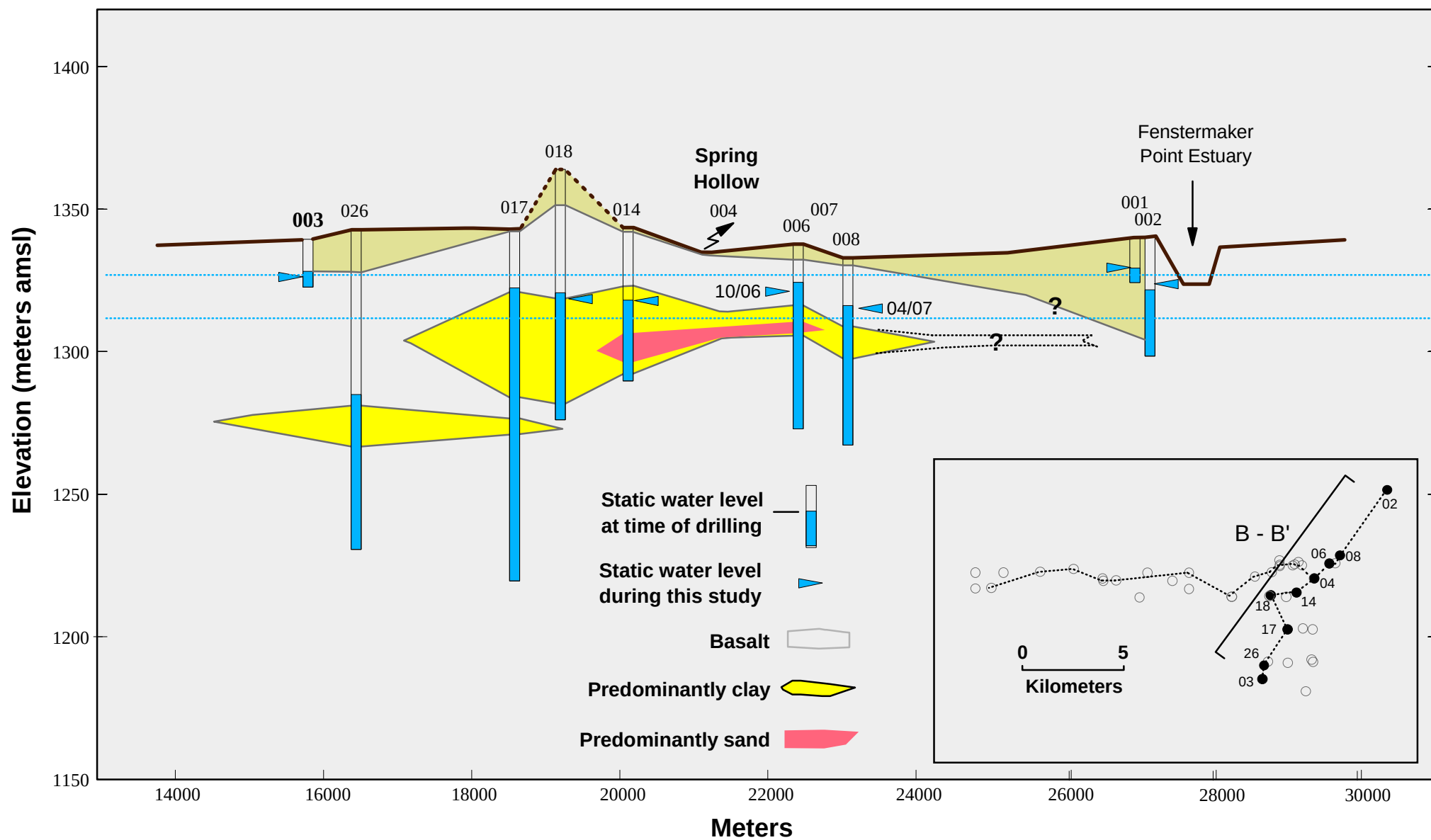


Figure 5b. Subsurface stratigraphy of the study area based on drillers' logs along section B-B'.

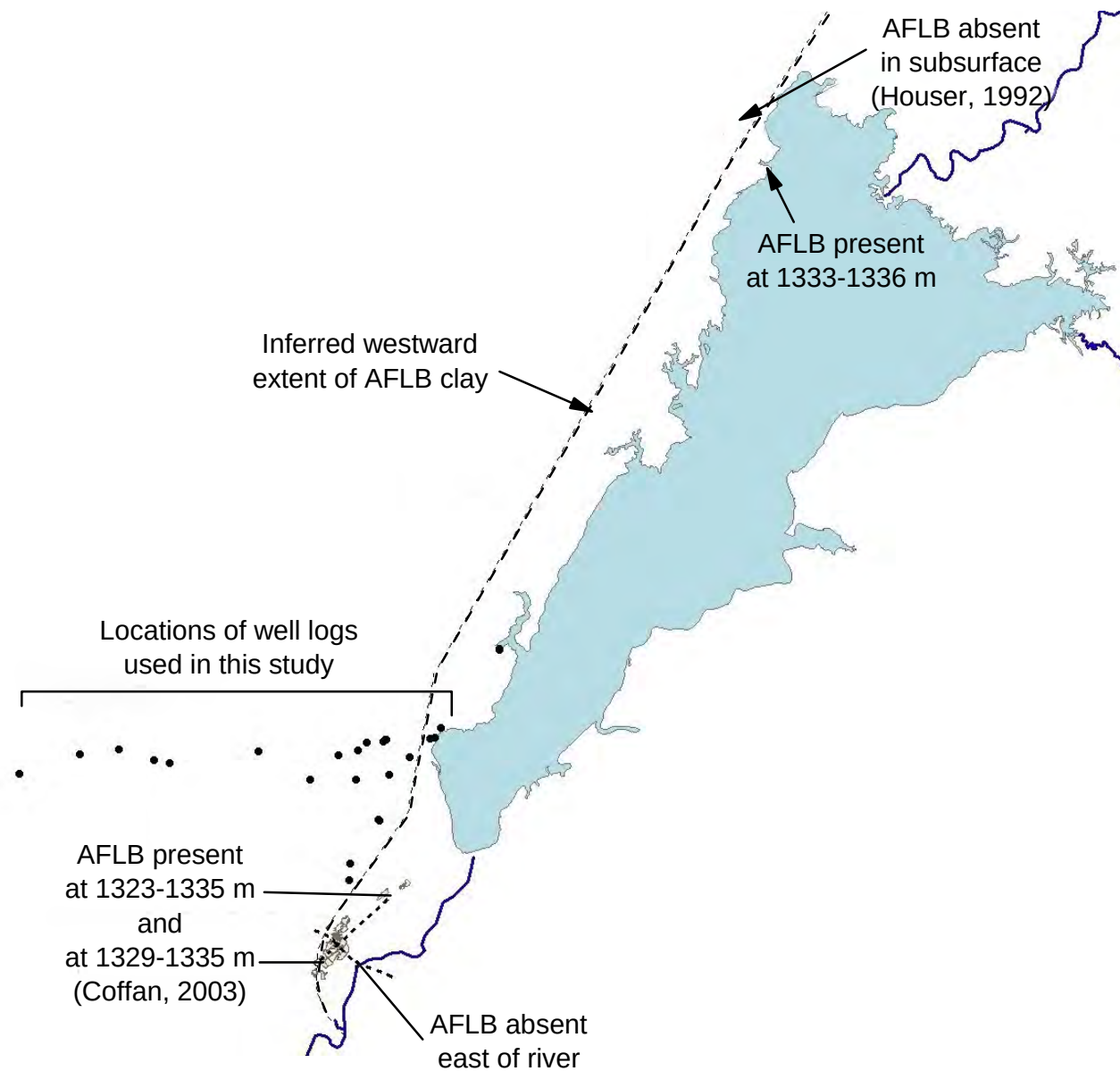


Figure 6. Known extents of the American Falls Lake Bed (AFLB) clay unit, after Coffan (2003) and Houser (1992), and its inferred westward extent based on Scott et al. (1982) and Castelin (1974).

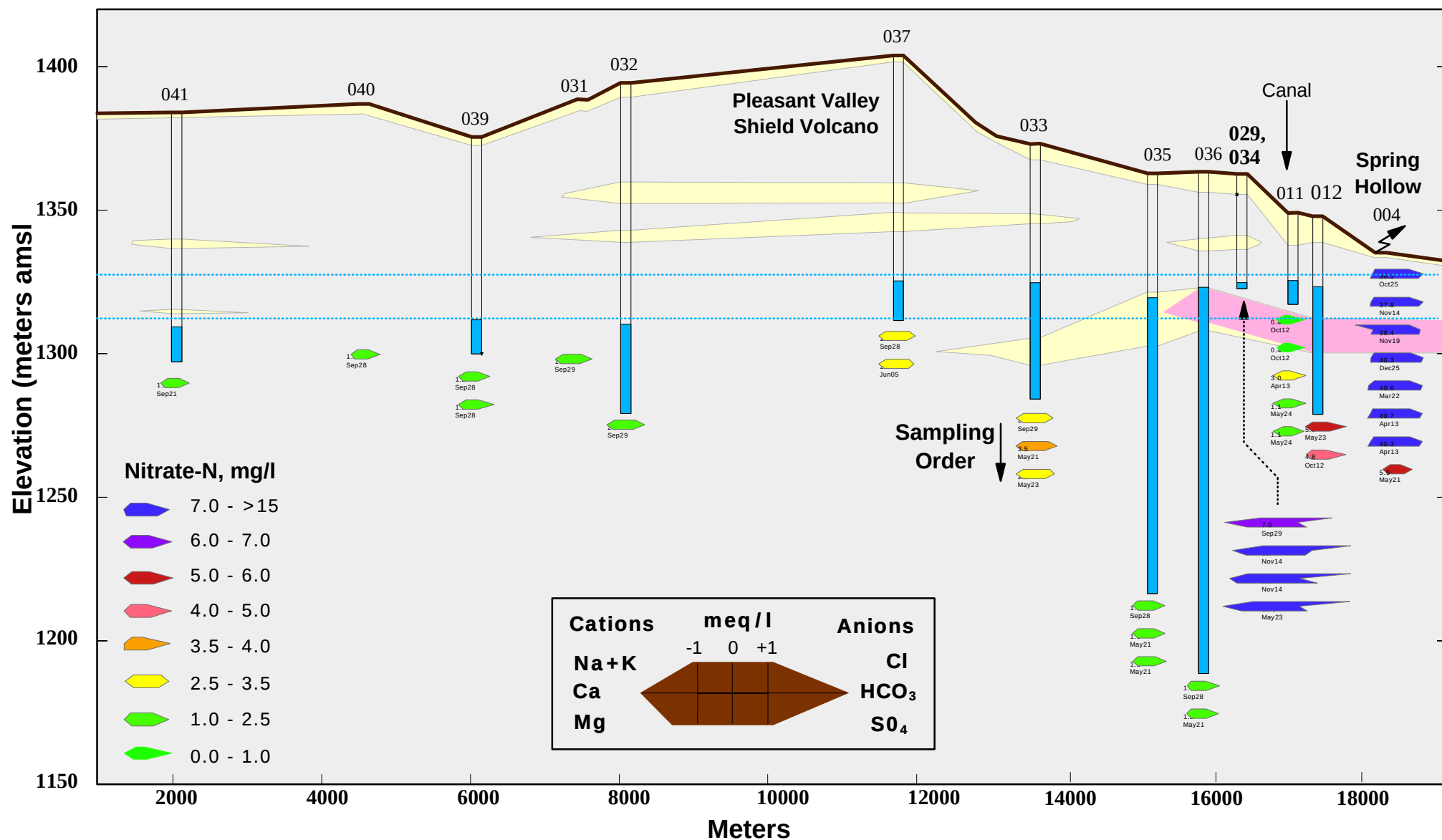


Figure 7a. Vertical distribution of nitrate and major ion concentrations, summarized as Stiff diagrams, along cross-section A-A'. See inset in Figure 5a for well locations.

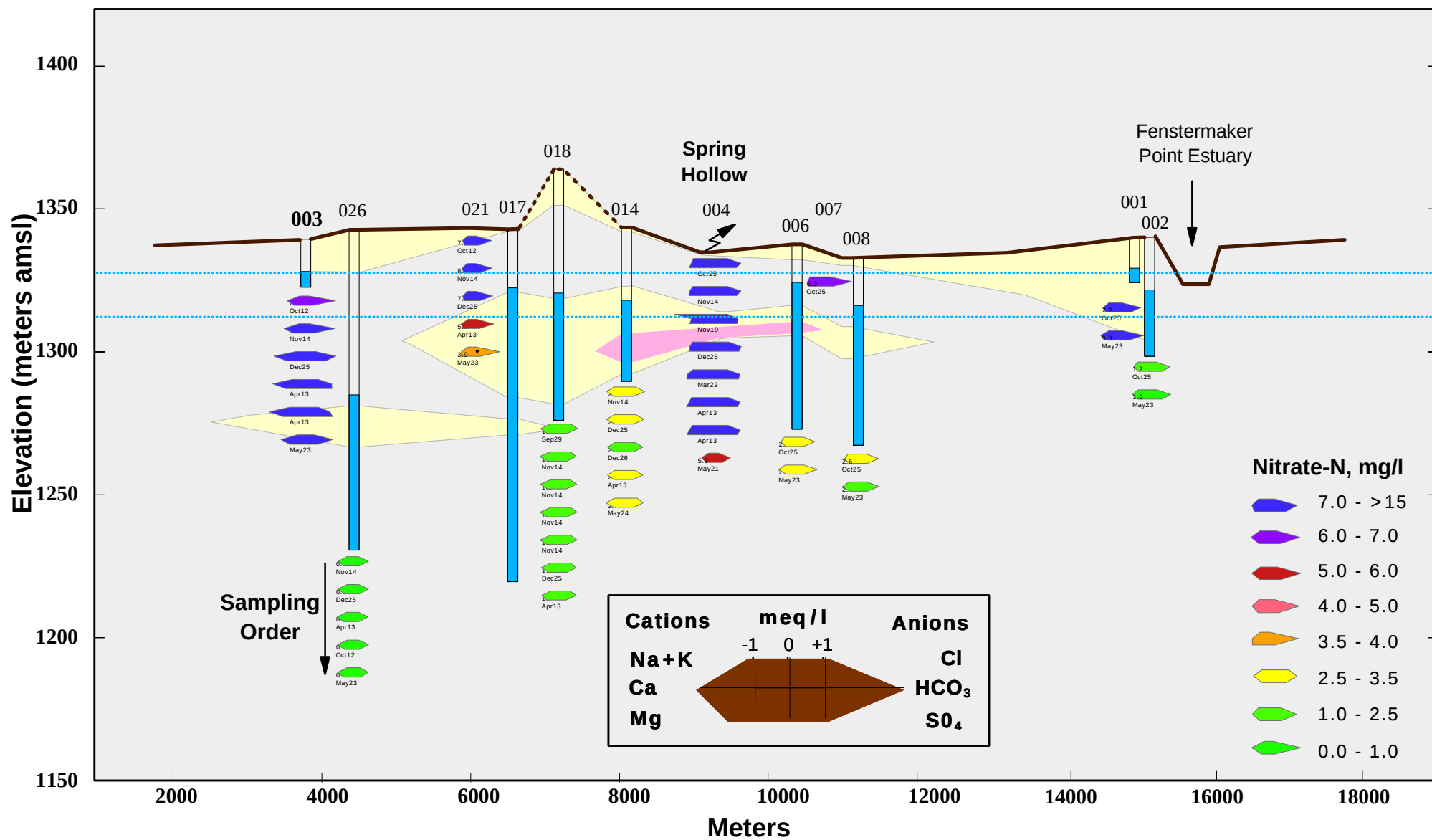


Figure 7b. Vertical distribution of nitrate and major ion concentrations, summarized as Stiff diagrams, along cross-section B-B'. See inset in Figure 5a for well locations.

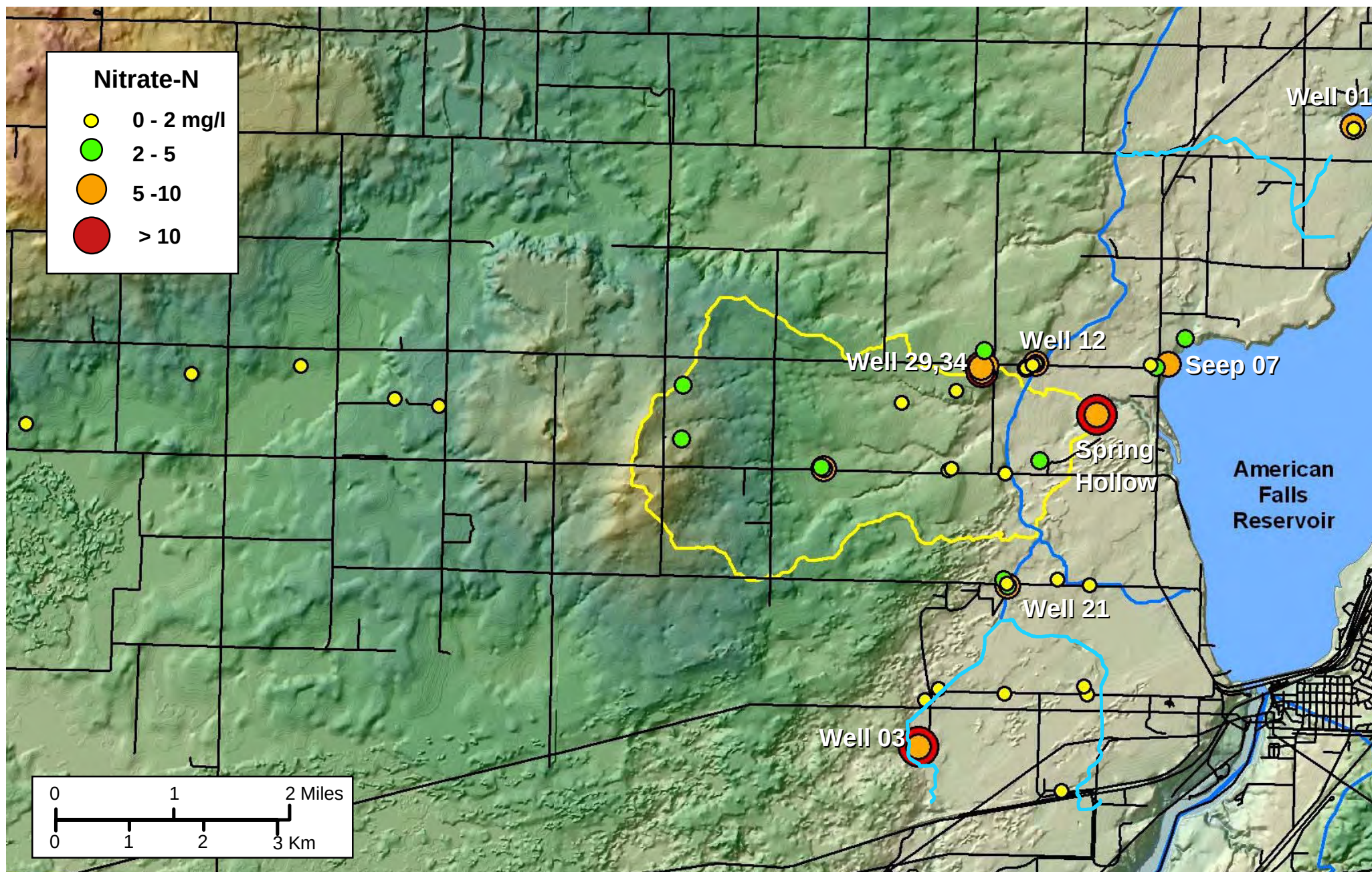


Figure 8. Geographic distribution of nitrate-N concentrations, in mg/l, observed in this study.

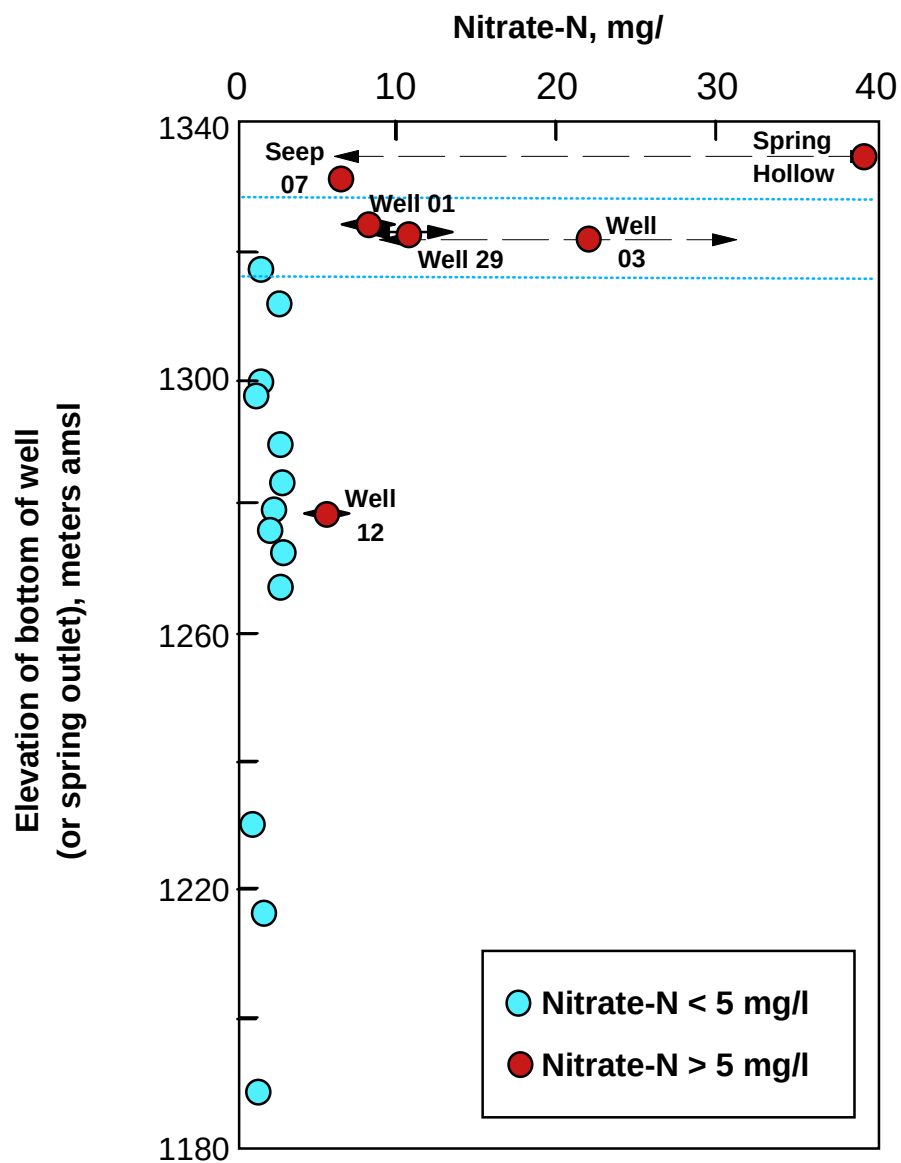


Figure 9. Vertical distribution of nitrate concentrations relative to range of variation of water levels in the reservoir. Plotted points represent the average and range of concentrations observed during multiple sampling events at each site; depths are for the bottom of the well, where available. Labels refer to locations in Figure 8.

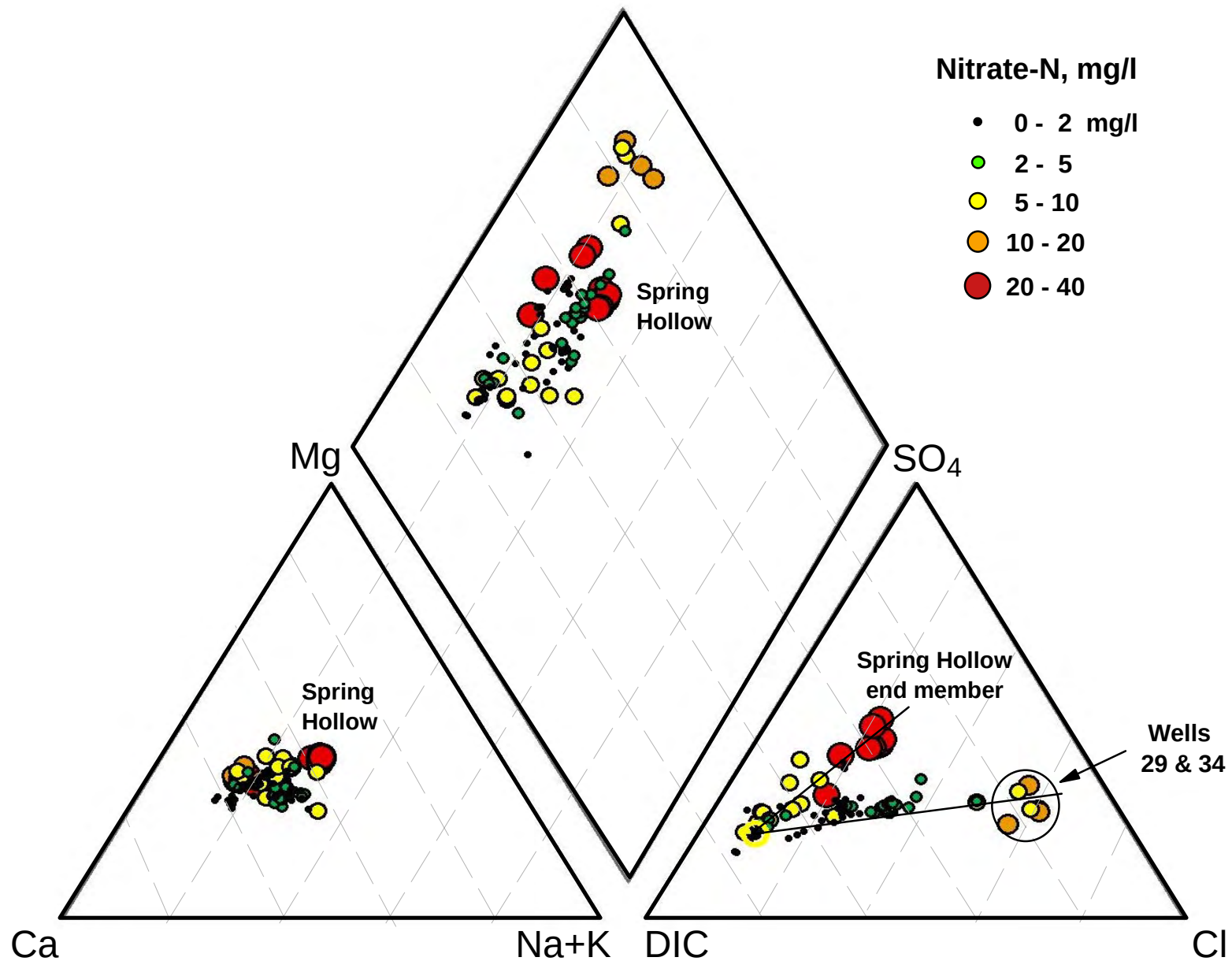


Figure 10. Variations in major ion chemistry, showing relationship between mixing trends and elevated nitrate-N concentrations in Cl- and SO₄-rich end members.

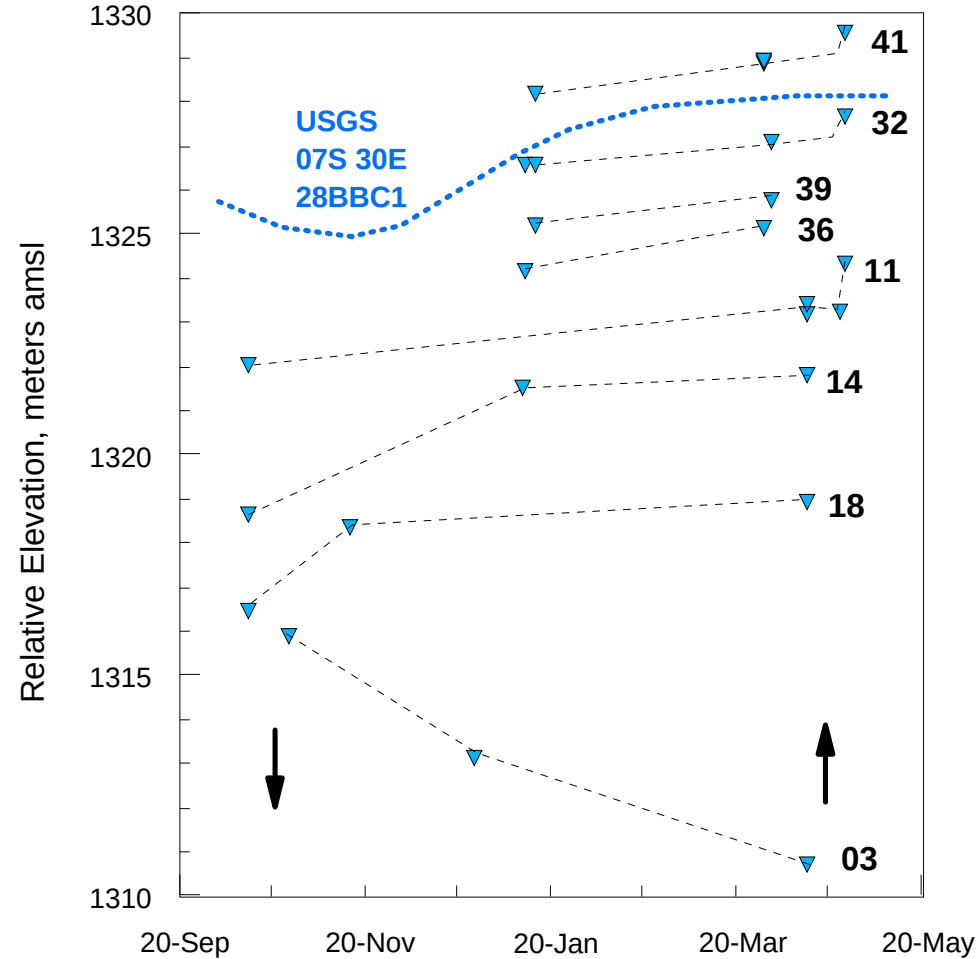
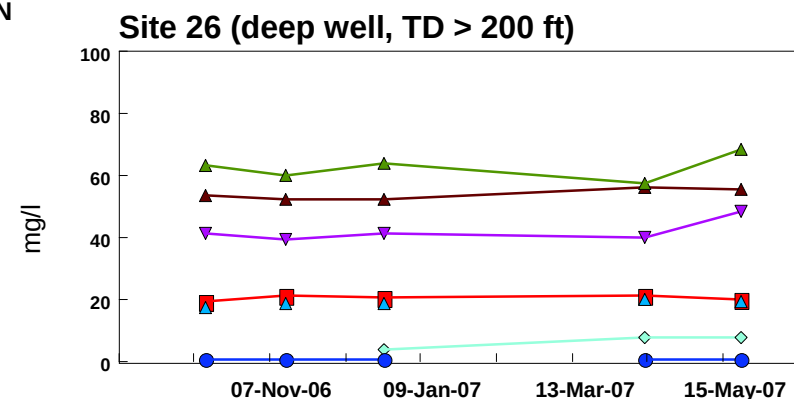
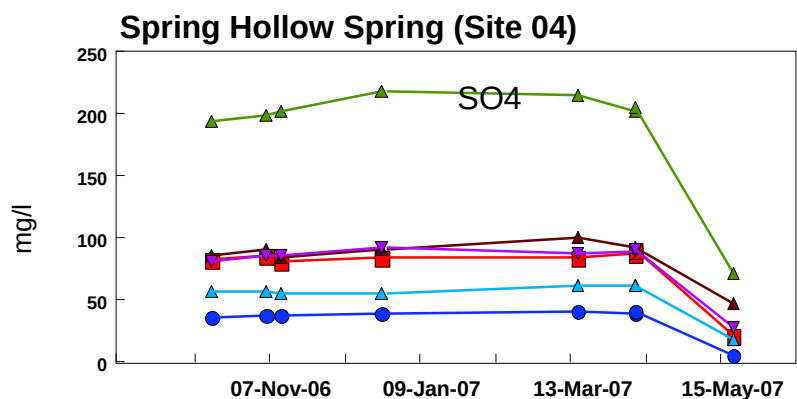
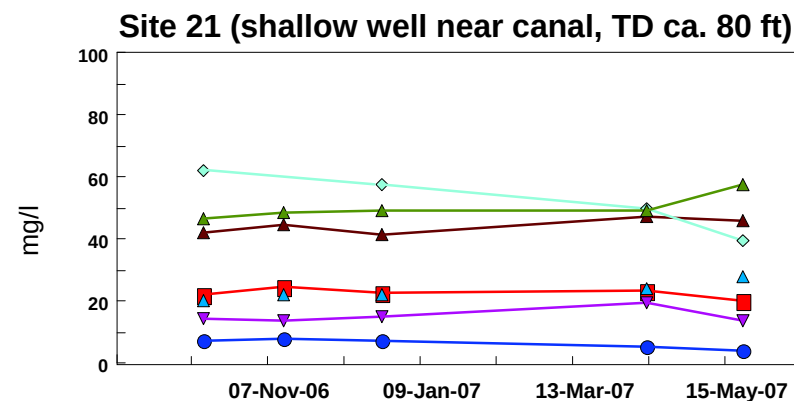
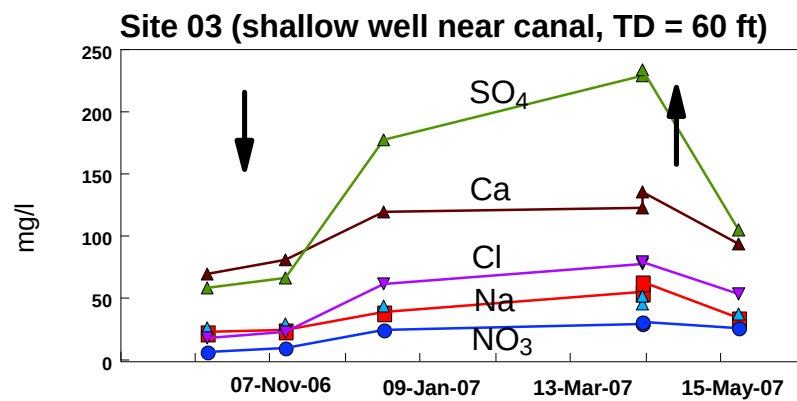


Figure 11. Relative static water level trends observed during this study. Wells identified by their site number. The seasonal response of a USGS monitoring well approximately six miles SW of the study area is shown for comparison. Arrows indicate approximate dates when local canals drained (down arrow) and filled (up arrow).



■ Na
 ▲ Mg
 ▲ Ca
 ▼ Cl
 ● NO₃-N
 ▲ SO₄

Figure 12a. Variations in major ion chemistry of selected wells and Spring Hollow. Arrows indicate approximately when canals drained (down arrow) and filled (up arrow).

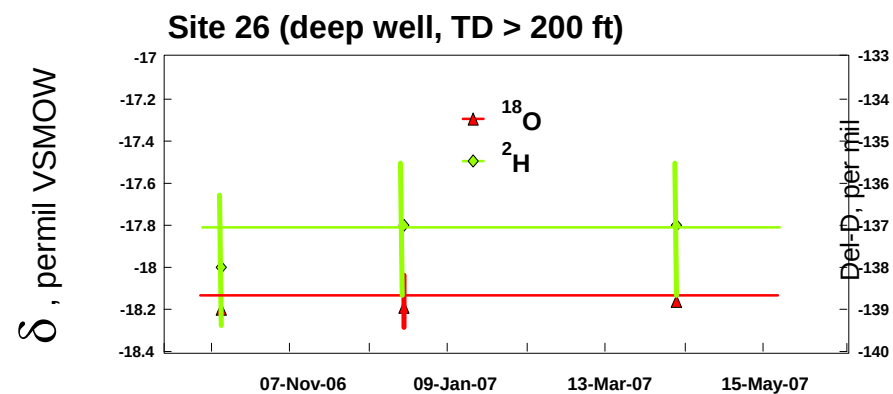
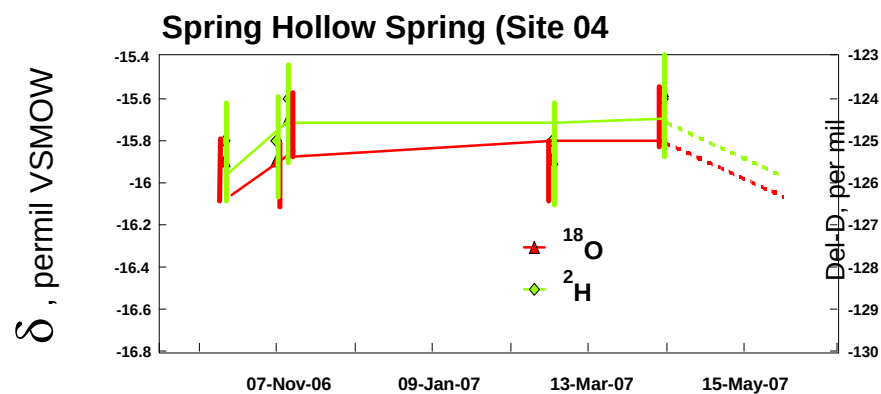
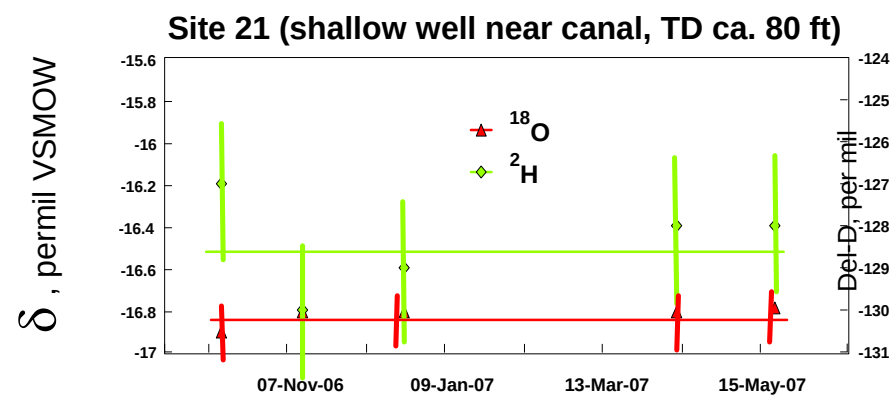
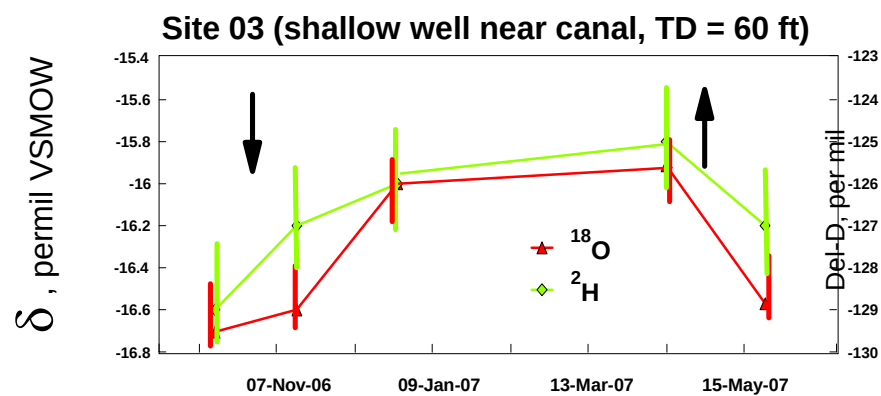


Figure 12b. Variations in stable isotope ratios of selected wells and Spring Hollow, in response to canal draining (down arrow) and filling (up arrow). Vertical bars indicate $\pm 2\sigma$ analytical uncertainty of isotope ratio measurements.

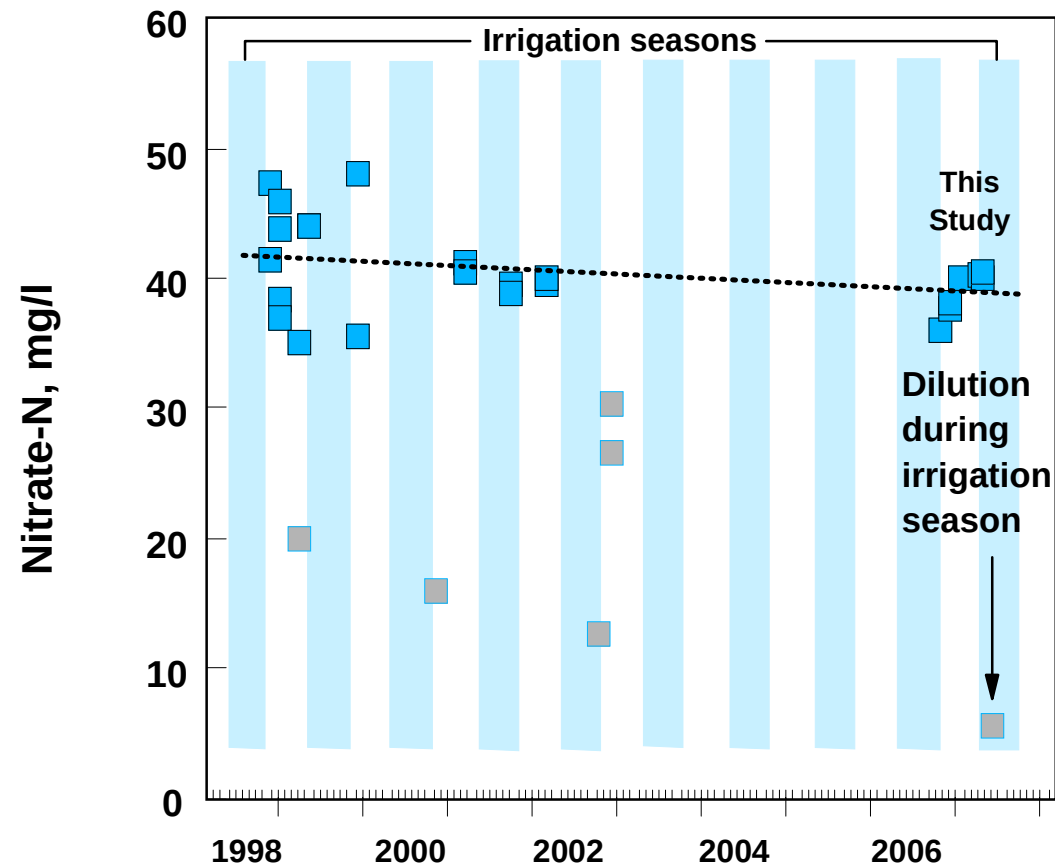


Figure 12c. All available nitrate concentration data for Spring Hollow, relative to approximate duration of irrigation seasons (vertical blue bars). Long-term regression trend ignores the lowest values (grey filled squares) as unrepresentative due to dilution by canal water. The regression slope is not significant at the 95% confidence level.

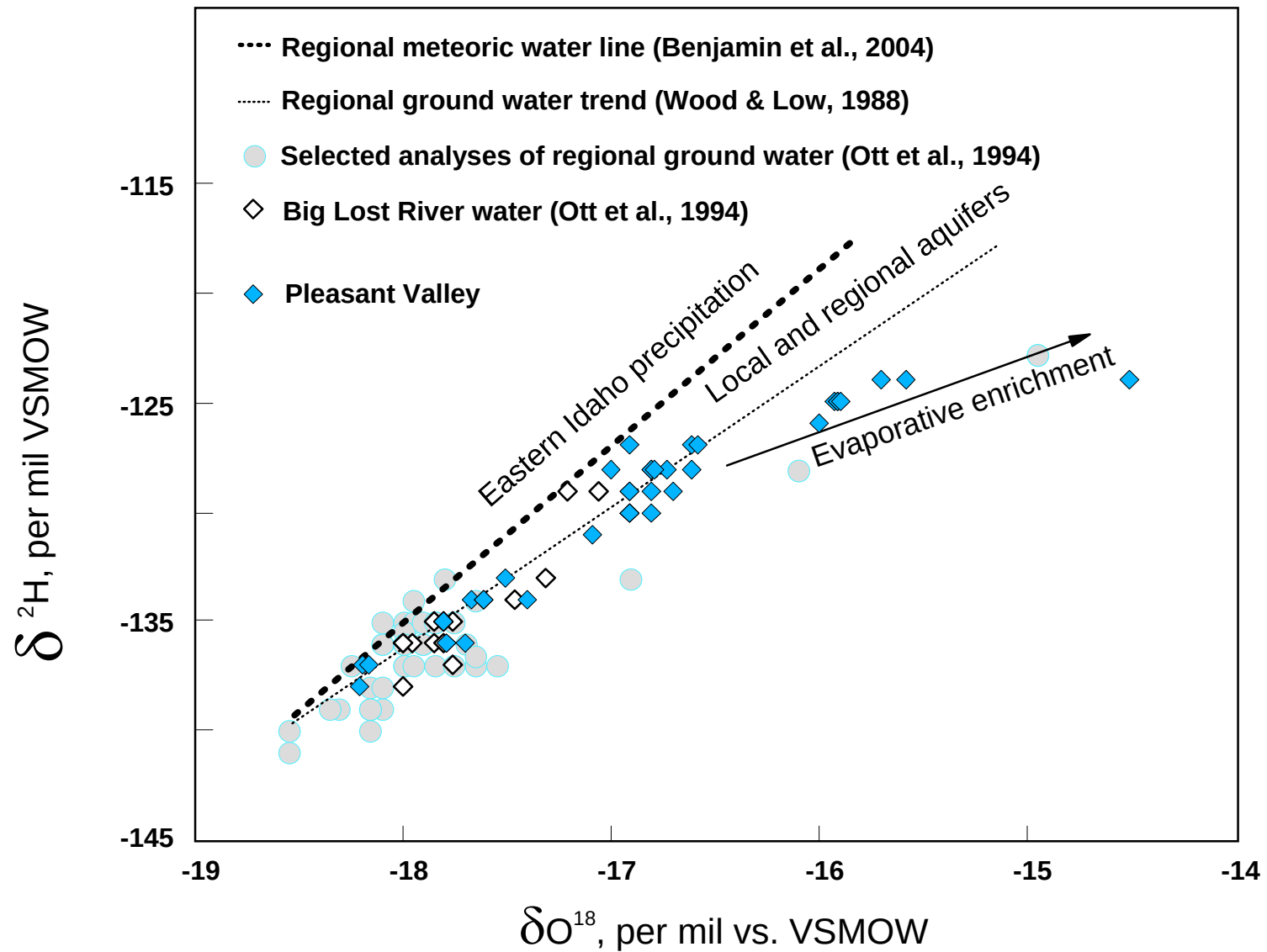


Figure 13. Stable isotope composition of Pleasant Valley waters compared to that of the eastern Snake Plain in general.

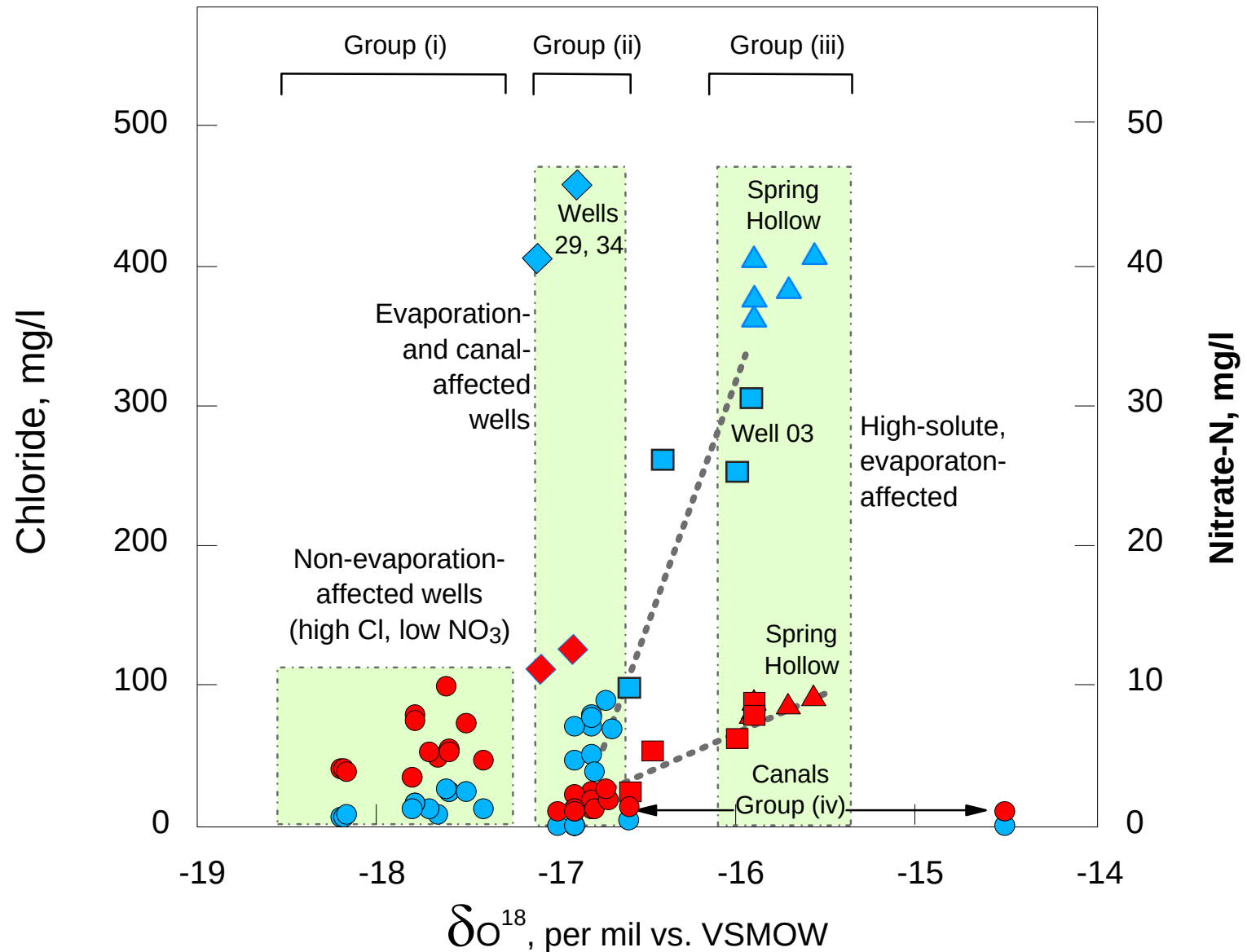


Figure 14. Classification of ground water sources based on chloride (red), nitrate (blue) and O^{18} content. Wells not affected by evaporation and canal water have $\delta O^{18} < -17.3$ permil. Inferred mixing trajectories between canal water and Spring Hollow end member are shown as dashed lines. Spring Hollow water compositions shown as (Δ); wells 29, 34 as ($\diamond$); well 03 as ($\square$); all other locations as ($\circ$).

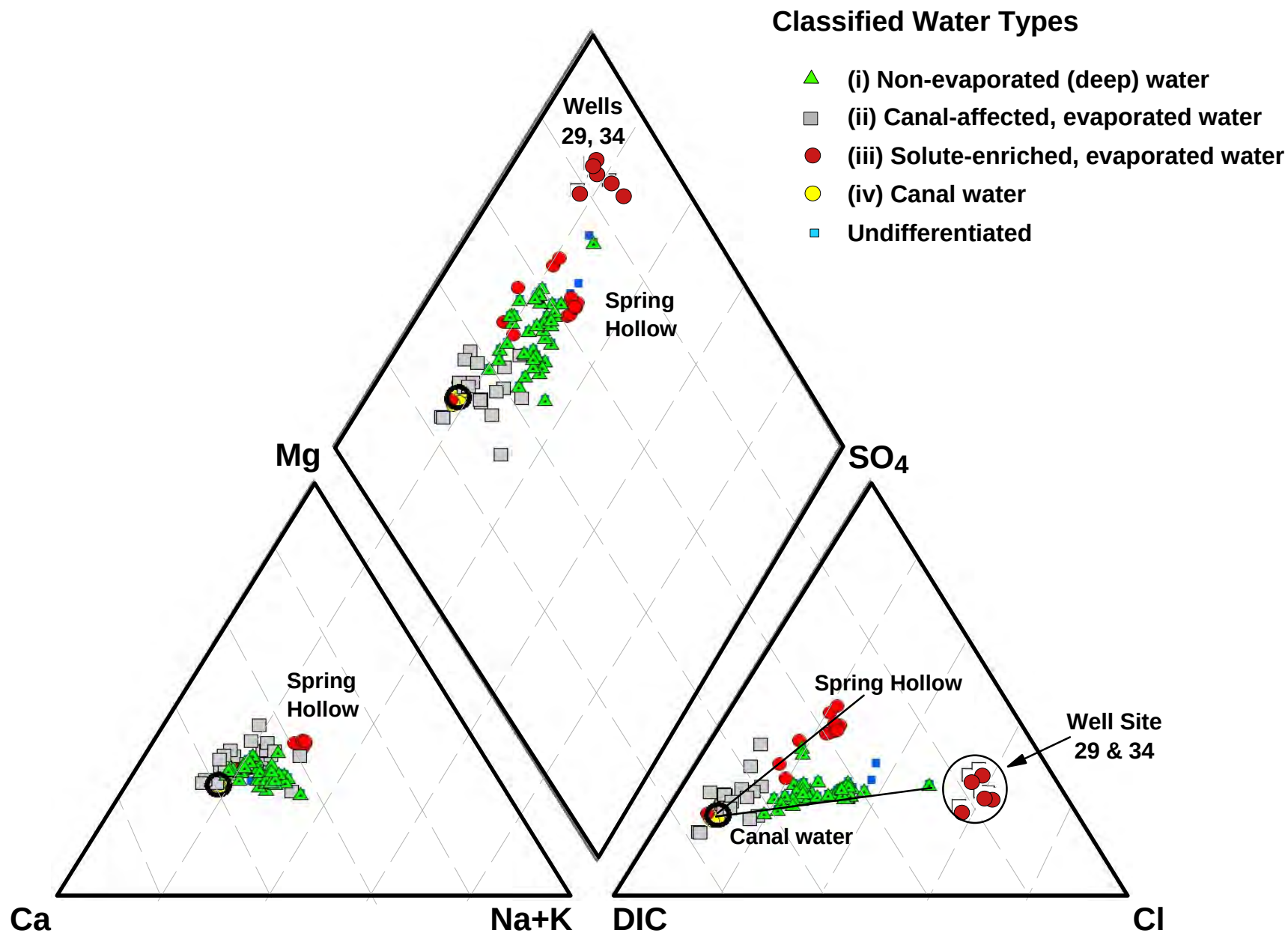


Figure 16. Deep regional ground waters (group i) define an anion mixing trend that is separate from waters that are slightly affected by evaporation-canal seepage (group ii) which define a mixing trend between canal water and the Spring Hollow end-member.

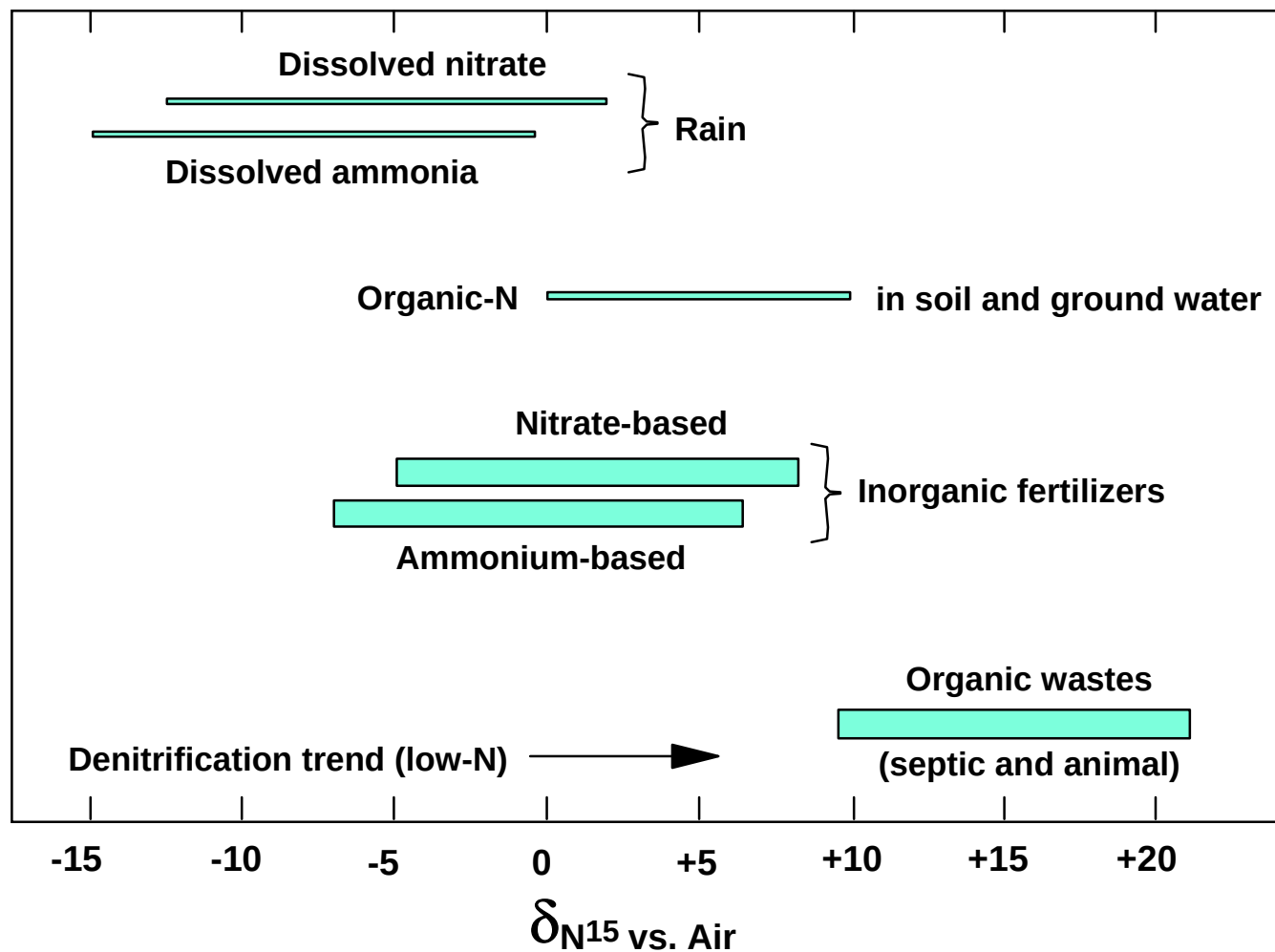


Figure 17. Nitrogen-isotope ratios that characterize common nitrate sources, after Heaton (1986). Of these, inorganic fertilizers and organic waste (septic and animal) are possible contaminating sources. Bar thicknesses indicate approximate relative nitrate concentrations that characterize these sources.

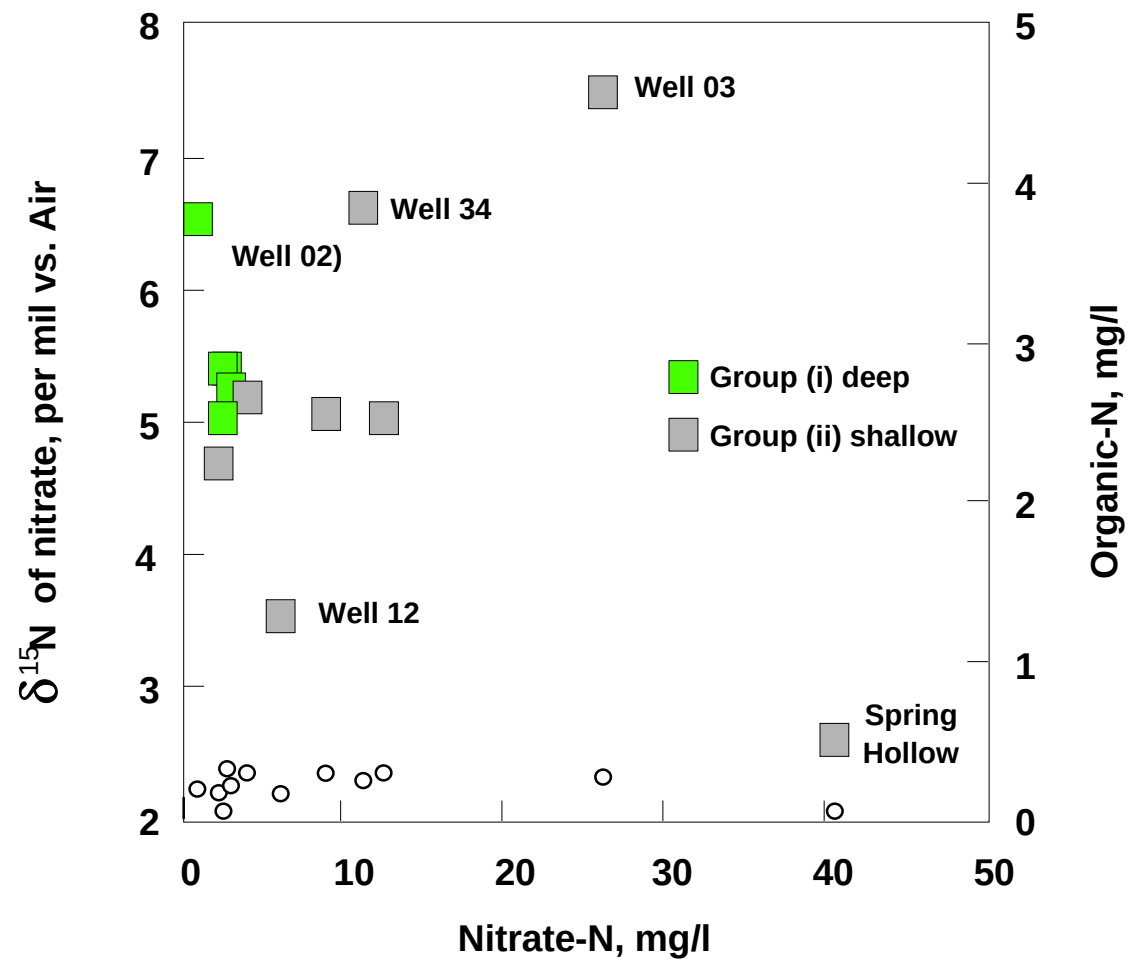


Figure 18. Relationship between δN^{15} of dissolved nitrate and concentrations of nitrate and organic-nitrogen in selected samples collected in April, 2007. All δN^{15} values have been corrected for possible interference by organic-N (cf. Section 2.5). N-isotope compositions plotted as ($\square$); organic-N plotted as ($\circ$).

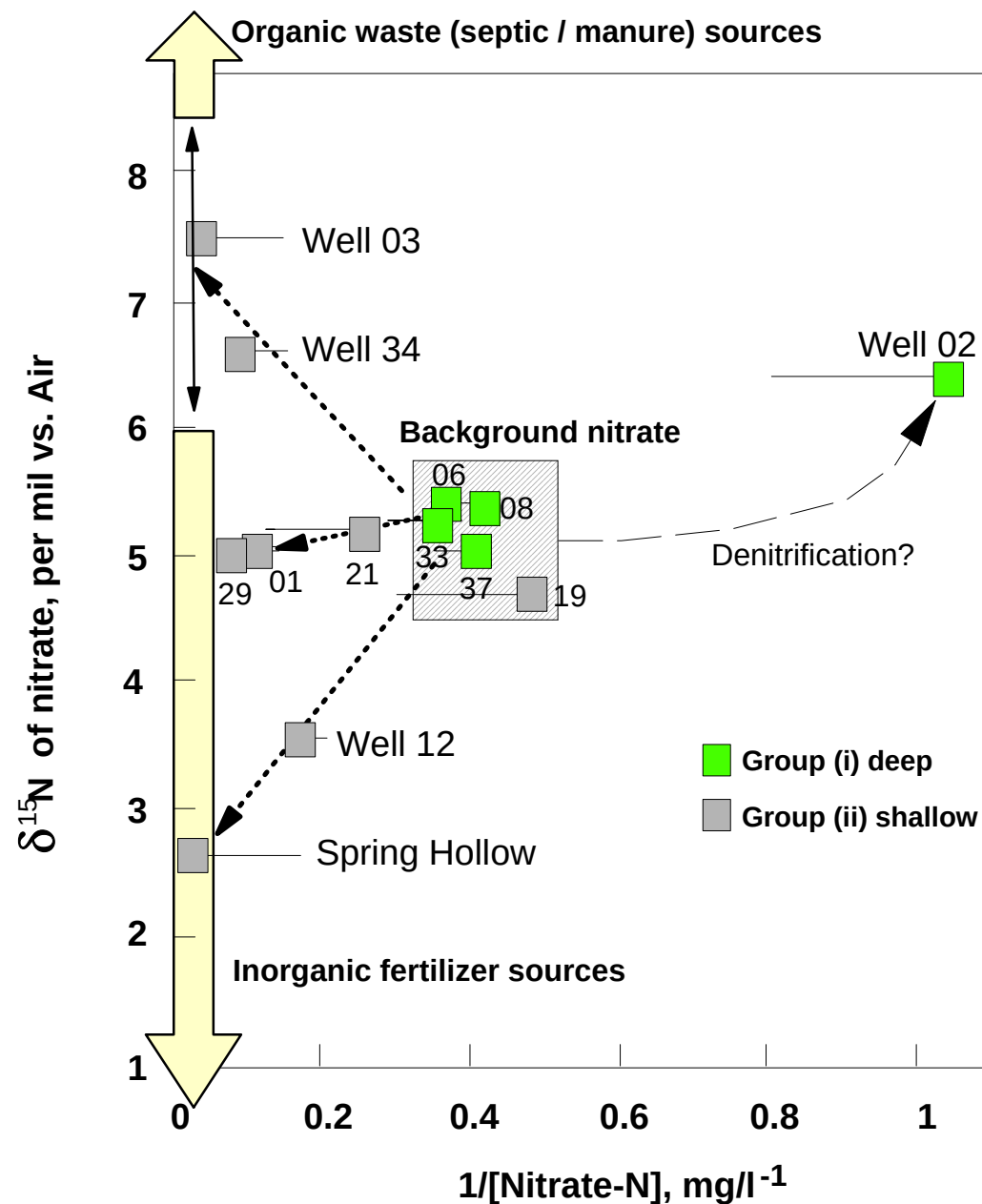


Figure 19. Nitrate mixing and possible source relationships inferred from N-isotope data. Vertical bars show the ranges of N-isotope compositions of inorganic fertilizer-derived nitrate and organic waste-derived nitrate (cf. Figure 17). Horizontal bars indicate the concentration range in samples collected at different times during this study.

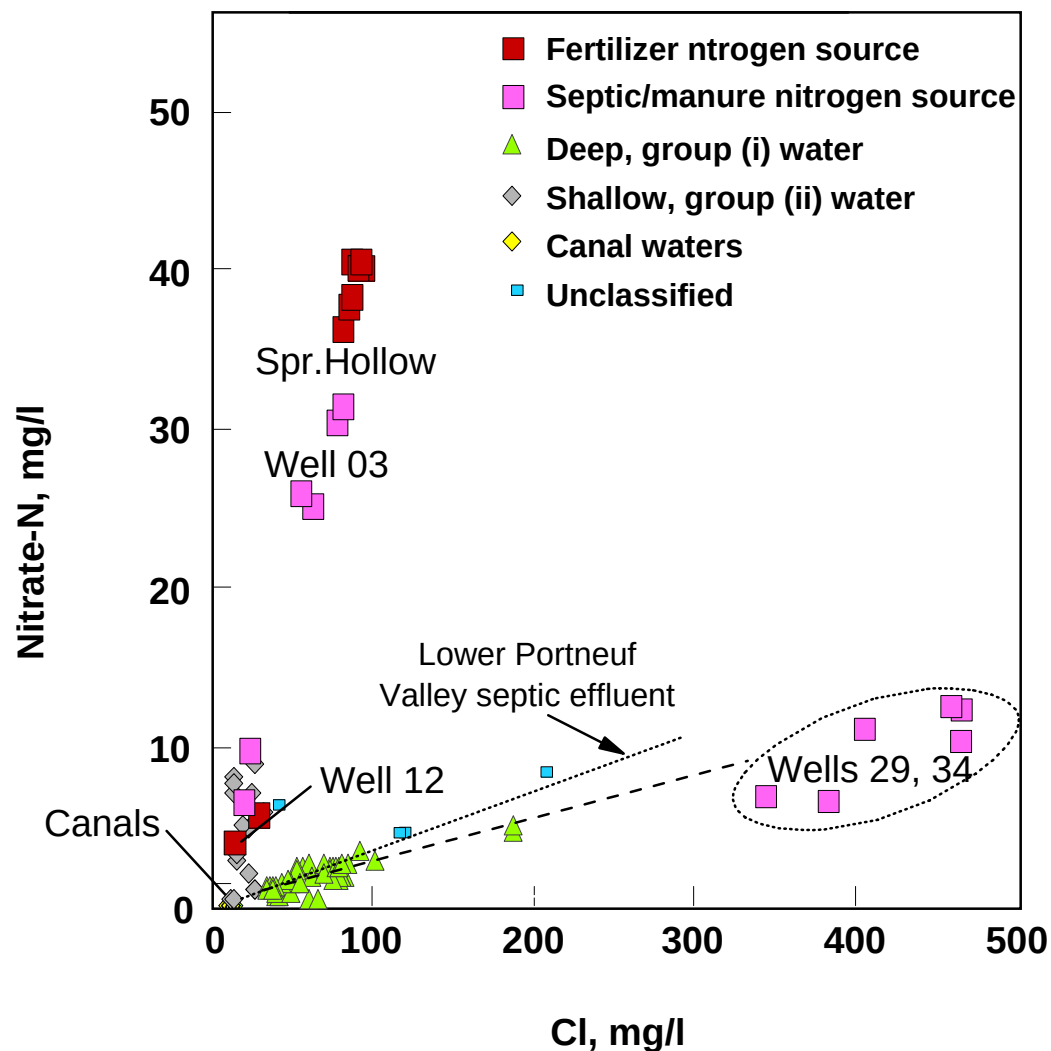


Figure 20a. Nitrate vs. chloride plot showing waters classified on the basis of anionic ratios, N-isotopes, chloride and oxygen-isotope data. The N-isotope composition in wells 03 and 34 indicates that nitrate in both is derived from organic waste but only well 34 (and 29) has anionic ratios similar to septic effluent (Welhan and Meehan, 2005).

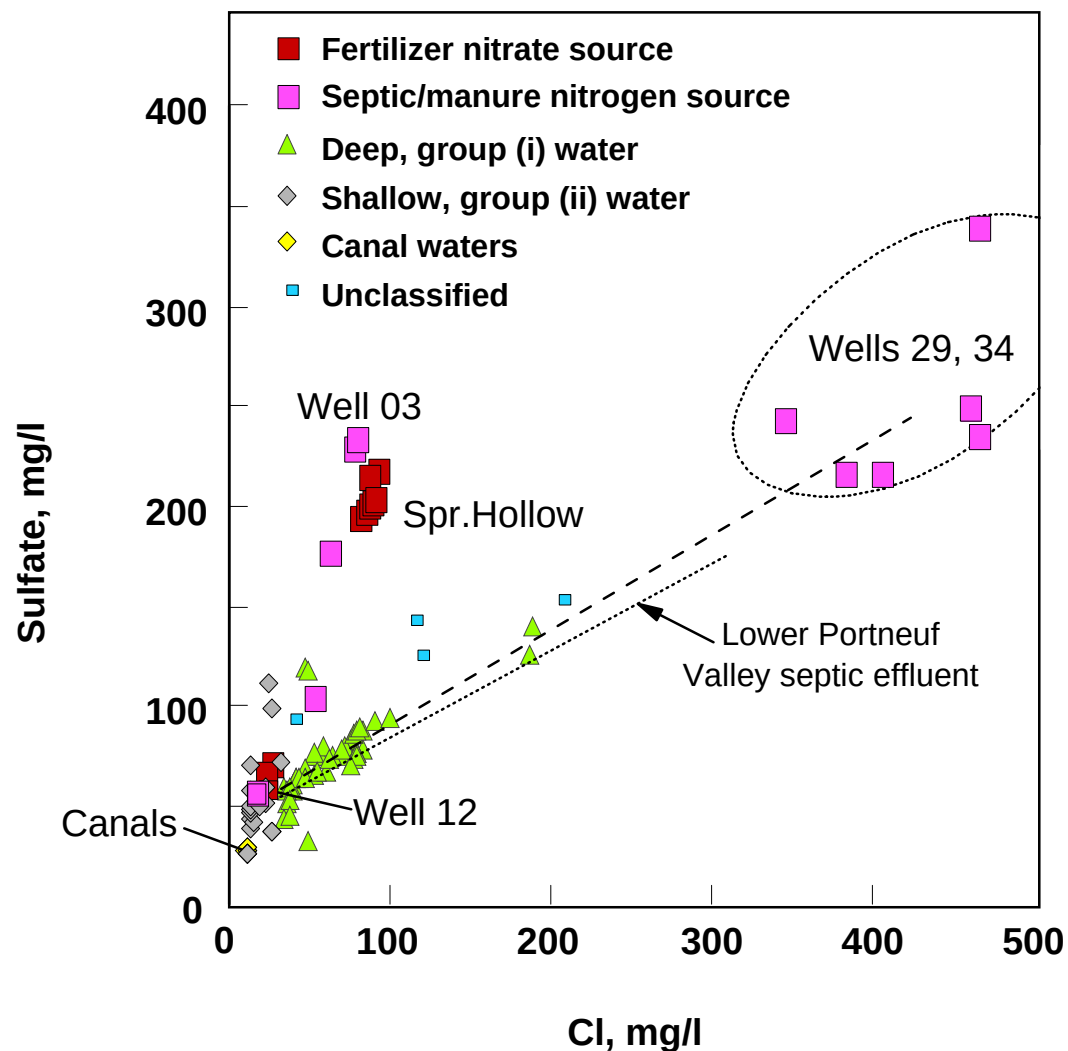


Figure 20b. Sulfate vs. chloride plot showing waters classified on the basis of anionic ratios, N-isotopes, chloride and oxygen-isotopes. The similarity of anionic ratios in group (ii) waters and septic effluent plus the dissimilarity to well 03's anionic ratios indicate that well 03's nitrate is derived from an organic source other than septic effluent.