

*Preliminary Assessment of
Hydrogeology and Water Quality in
Ground Water in Canyon, County,
Idaho*

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Introduction

This report is the second of two reports documenting a preliminary investigation of the geology and hydrogeology in the Canyon County, Idaho area done by the Idaho Water Resources Research Institute (IWRRI) for the Idaho Department of Environmental Quality (IDEQ). The companion report, Preliminary Geology of the Northwestern Portion of Canyon County, Idaho, IWRRI Technical Report 20051, April, 2005, documents the geology of the study area. This report documents the preliminary hydrogeology and water quality investigation done for the study area.

IDEQ initiated this work in 2004 due to several concerns. The high rate of housing development in Canyon County, Idaho is causing mounting concerns over the potential introduction of water quality problems due to the installation of domestic onsite wastewater systems. An assessment of the area hydrogeology is necessary to evaluate Nutrient-Pathogen (N-P) Level 1 analyses submitted by developers (Howarth, et al, 2002). The N-P Level 1 evaluations include a spreadsheet analysis which requires hydrologic characteristics as input values.

The second primary water quality concern in the study area is the occurrence of radionuclides, particularly uranium, in the aquifer. Uranium concerns in Canyon County stem from previous water quality analyses indicating high concentrations of uranium in some locations. Because few water samples have been analyzed for uranium, the extent of the problem is largely unknown.

Although nitrate concentration levels due to onsite wastewater systems and the high concentrations of uranium are the primary concerns, IDEQ is also interested in characterizing other contaminants (arsenic and thermal waters) to determine whether other water quality problems exist and to baseline the water quality in the study area. In 2000, the 1977 Radionuclide Rule for community public water systems was revised to include a requirement to test for uranium, effective in 2004 (Environmental Protection Agency, 2003). Table 1 lists selected maximum concentration levels (MCLs) and maximum contaminant level goals (MCLGs) published in 2003.

Objectives

This pilot project study area comprised four townships of the total of 16.8 townships in Canyon County. The project was intended to provide a proof of method and guidelines for future investigation of water quality issues in Canyon County, Idaho.

Specific objectives of the project include:

- a) provide a general hydrologic characterization of the four townships being studied,
- b) for the upper-most fifteen feet of saturated strata, provide maps of aquifer storage and hydraulic gradient,
- c) evaluate the potential of using existing pumping test data in support of the hydrologic characterization,

- d) analyze water quality in twenty wells in the study area to provide initial evidence of the spatial and vertical distribution of uranium and to baseline water quality in the region and
- e) evaluate whether it is feasible to identify specific water-bearing strata which contain high concentrations of uranium.

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Study Area Description

The study area comprises four townships in the north-central portion of Canyon County. The four townships in the study area are T4N R2W, T4N R3W, T5N R2W AND T5N R3W. The study area, the county boundaries and their location in the State of Idaho are shown in Figure 1. The Boise River flows from east to west through approximately the north-south center of the southern two townships (T4N R2W and T4N R3W). The city of Caldwell, Idaho, population 26,000, is located near the center of the township T4N R3W, south of the Boise River. The town of Middleton, Idaho (population 3,000) is in the northwest corner of T4N R2W, north of the Boise River. The town of Star, Idaho, population 2,000, is just outside of the study area to the east of the same township.

Canyon County has been predominantly rural with extensive farming. Population centers have some industrial activity, primarily associated with agriculture. The northeast corner of T5N R2W contains foothills with little housing or agricultural activity. Caldwell, Idaho is approximately 30 miles west-northwest of Boise, Idaho. The explosive growth in the greater Boise area has caused a ripple effect of development in the Caldwell area and in Canyon County in general.

Methods

Drillers' logs were extensively used to determine the spatial extent of perched and regional aquifers and descriptions of the lithology in saturated zones. The hydrologic characterization also relied on previous hydrologic studies (discussed below) in the surrounding area.

The water quality component of this study included a review of existing water quality data in or near the study area, and sampling and analysis of water from wells in the area. Additionally, rock samples were collected from an outcrop of a formation suspected of being the source of the uranium. These samples were analyzed for uranium content.

Collaboration with Boise State University Arsenic Study

Once this current study was underway, the researchers learned of a similar effort on the part of hydrologists at Boise State University (BSU) to investigate the occurrence of arsenic in a study area similar to the current study. Discussions with BSU hydrologists indicated that there was some overlap in areas of interest and that both projects would benefit through collaboration. BSU conducted much of the field work for both studies (initial field work for the ongoing BSU study and final field work for the current study) in exchange for IWRI conducting the water quality sample analysis. By collaborating, we were able to increase the number of samples analyzed for this current study from the contracted 20 samples to 27 samples.

Analysis of Area Hydrogeology for Nutrient-Pathogen Analyses

This section of the paper discusses the analysis of the hydrogeology of the study area. Area hydrogeology is discussed, as well as the use of drillers' logs to determine hydrological characteristics of the top 15 ft of saturated zone for use with N-P Level 1 evaluations. Maps of the major hydrological characteristics are presented.

Overview of Study Area Hydrogeology

The geology of the study area is dominated by lake and river deposits and is documented in the companion report to this current report (Otto, 2005). The study area has a complex ground-water environment which is described in detail by Hutchings and Petrich (2002). The regional aquifer is generally confined or semi-confined and is overlain by several hundred feet of interbedded sands, silts and gravels, many of which are water-bearing. There is significant vertical stratification in these sediments, with productive confined and unconfined aquifers interspersed with less permeable sediments. There is thought to be little vertical communication between the various water-bearing strata, as confirmed by distinct water quality signatures (Hutchings and Petrich, 2002).

Many drillers' logs in the study area show a distinct sediment color change between brown/yellow sediments and blue/gray sediments. This color change is interpreted by Hutchings and Petrich (2002) to possibly indicate a transition between surficial alluvial deposits (oxidizing) and deep lake deposits (reducing).

Recharge to the study area aquifers is dominated by applied irrigation water and canal seepage. The Boise River is the source of much of this irrigation water; however, water is imported from the Payette River to canals in the northeast portion of the study area. Additional recharge comes from precipitation and from underflow from adjacent aquifers and tributary basins.

Data from Drillers' Logs

Data from approximately 3,000 drillers' logs were entered into a data base. The data include well location, completion depth, screened intervals, static water level and top, bottom and lithology of the first three water-bearing strata. The reader is cautioned that there are very few controls on the quality of the data in drillers' logs. The drillers' logs do, however, provide an overall picture of the regional subsurface which is not available

elsewhere. Individual logs which were incomplete or which represented shallow monitoring wells were not added to the data base. The overall number of drillers' logs used to construct the data base was sufficiently large to provide a good spatial distribution of subsurface data. It is hoped that the large number of logs used should also serve to countermand data from logs which might contain incorrect data. Figure 2 shows the distribution of wells for which data were entered into the data base.

Onsite Wastewater Disposal Issues

Many of the subdivisions planned within the study area and Canyon County at large rely upon the installation of private onsite wastewater treatment systems. These onsite wastewater treatment systems may utilize the standard septic tank, or the more recently approved category of aerobic treatment systems, depending upon the site conditions and facility wastewater characteristics. Both the septic and aerobic systems consist of an underground tank and associated drain field. Household waste enters the tank on one side and processed waste exits to the drain field on the other side. The processing includes solid and liquid waste separation and microbial waste reduction. Treated liquid waste is either gravity or pressure dosed to the drain field. When the onsite system is in constant use, the drain field is continually moist. This condition encourages the development of a microbial mat, referred to as a biomat, which acts as a tertiary filter reducing residual nutrients prior to encountering ground water.

Site characteristics impact not only the type of onsite wastewater system permissible, but also the size of the system required to adequately process the wastewater. The soil type where the drain field is located will impact the drain field size. Tight soils, such as silts and sandy clays, will require a larger area in order to effectively accept the wastewater volume at the lower infiltration rates associated with these soil types. Depth to and quality of the site's ground water will impact whether a standard septic system is permissible or whether an advanced onsite aerobic treatment system will be required. Typically, where ground water quality has not been degraded and the depth to ground water exceeds 10 feet, a standard septic system may be allowed. Otherwise, an advanced onsite aerobic treatment system may be required to reduce the nutrients and other constituents sufficiently to protect the ground water from significant degradation.

All domestic wastewater contains pathogenic microorganisms (bacterial, protozoan, viral, and helminth ova), nitrate, phosphate, pharmaceuticals and personal care products, and synthetic organic molecules from household cleaners. These effluent constituents are either processed in the onsite system, sequestered in the precipitated solids in the tank, filtered out in the biomat, or adsorbed to soil and mineral particles beneath the drainfield. The wastewater may entrain some of these constituents, and given enough time, these constituents may migrate through the vadose zone and encounter the regional or sub-regional aquifer. An overloaded or poorly maintained onsite system, or too many onsite systems in an area, may cause these constituents to reach the aquifer more quickly, although local regulation should preclude permitting of onsite wastewater systems in densely populated areas.

DEQ and the Health Districts may require a developer, through their professional engineer or a professional geologist, to perform a Nutrient – Pathogen (N-P) Study. An N-P Study is a conservative evaluation of the proposed development’s potential for impacting the quality of underlying ground water and/or adjacent surface water. This is accomplished through modeling the development’s discharged wastewater, taking into account the volume, concentration of constituents, and location of these discharges, and evaluating how it interacts with the site’s ground water. Site attributes identifying the ground water flow include hydraulic conductivity, the aquifer’s gradient, and the ground water constituent concentrations. Additional site attributes that will influence the model’s results may include, but are not necessarily limited to, the rate that rain or snow recharges the aquifer, and the volume and quality of infiltrating irrigation water. These variables are all combined in either simple arithmetic models, or may be analyzed in more complex numeric or fate and transport models commonly available to ground water hydrology professionals.

Based upon the N-P guidelines defining an ‘area of concern’ as “an area where the soil depth is shallow or there exists a predominance of gravel or other coarse-grained sediment, as shallow depth to ground water (10 ft or less)...,” the health district or DEQ may require that a N-P Study be completed. Much of the study area is underlain by coarse gravels and shallow ground water, heightening concerns about onsite wastewater system siting. In this situation, the N-P Study must show that the ground water is not significantly degraded, and any adjacent surface water is suitably protected.

Analysis of Pumping Test Data

In a similar study conducted in the Greanleaf, Idaho area (Otto and Wylie, 2003), pumping tests recorded on the drillers’ logs were used to assist in characterizing the hydraulic conductivity of the top-most saturated layer. The stratigraphy in the Greanleaf area is such that strata which are exposed in some areas are deeply buried and water-bearing in other areas. This means that the same stratum, which is the water-bearing zone in one part of the region, may also represent the top-most saturated zone in another part of the region and be exposed at the surface in yet a third part of the region. Pumping tests conducted by drillers are always conducted in the most productive water-bearing zone, where the well is completed.

In the current study area, the stratigraphy is comparatively flat. There are very few ground-level exposures of strata which are otherwise buried. An exhaustive analysis of the drillers’ logs in the current study area showed that the pumping tests were always conducted in a saturated zone well below the top-most saturated layer, the layer of concern for onsite wastewater system contamination. This means that, although some inference can be made of sub-surface properties from the recorded pumping tests conducted by drillers, this is not representative of the upper-most saturated layer. Due to the lack of viable pumping test data, the current analysis of hydrologic characteristics was based on lithology descriptions from drillers’ logs.

Hydrologic Study Results

Depth to Water

The drillers' logs were analyzed for depth to water. In a less complex hydrologic regime, the meaning of depth to water would be clearer. However, in the study area, the complex layering of saturated and unsaturated zones presents a challenge for interpretation. Discussion with IDEQ (personal communication, T. Neace, 2006) indicated that a reasonable interpretation of depth to water would be the depth to the first water-bearing zone with a saturated thickness of 10 ft or greater. Depth to water for the individual wells in the drillers' log data base were interpolated using a kriging method in ESRI Arc-Map 9.0 to generate a map of the spatial distribution of depth to first occurrence of water. Figure 3 shows the map of the depth to first occurrence of water in the study area, using the stated criteria.

Inspection of Figure 3 shows that shallow depth to water (40 ft or less) occurs in much of the study area, particularly near the Boise River. Figure 4 shows the location of wells which report a depth to water of 10 ft or less. There are two probable explanations for the shallow depth to water near the river. River seepage is likely recharging the area. In addition, irrigation diversions from the river flow through canals throughout the study area. Clay lenses between the regional aquifer sediments trap seeped water, causing perched saturated zones. Canal leakage and applied irrigation water potentially contribute to the shallow depth to water at these perched zones.

The elevation of the top-most occurrence of water (again using the criterion of 10 ft or more of saturated zone) was estimated by subtracting depth to water from land surface elevation. Land surface elevation was obtained by intersecting well locations with USGS 10 m digital elevation maps (DEMs) (USGS, 2006b). From previous work, it has been determined that the 95% confidence interval on deriving elevations using 10 m DEMs is estimated at 1.21 ft +/- 1.17 ft (Wylie, 2004). The estimated elevations for the top of the first occurrence of water for the wells in the drillers' log data base were interpolated using a kriging method in ESRI Arc-Map 9.0. Figure 5 shows a map of the elevation of the surface of the first occurrence of water for the study area. It should be noted that it is not certain that this saturated zone is a continuous zone. Hence, the reader should use some caution when interpreting Figure 5 as localized conditions could differ.

Gradient

The gradient of the top of the saturated zone was estimated using the ESRI flow direction tool, which is part of the ESRI surface analyzer tools. Figure 6 shows the gradient of the shallow water in the study area. Figure 6 shows a high degree of variability of localized gradient, particularly in areas where the overall gradient is very shallow (less than 1 ft/ft). Because the gradient was based on the first occurrence of water as documented in the drillers' logs, it should be noted that the first occurrence of water may not be spatially contiguous. Therefore, the gradient map is expected to contain some inaccuracies.

Porosity

Rock porosity is an estimate of the ratio of connected pore space to solid rock in a stratigraphic section. For example, a porosity of .2 indicates that 20% of the volume of the section is pore space and 80% is rock mass. A low porosity indicates a denser rock type with less pore space. Igneous rocks such as granites tend to have lower porosity. Gravels tend to have higher porosity. The porosity of a mixed layer (such as the sand and gravel found in many of the strata of the study area) will tend to be lower than pure gravel because the sand fills the interstices among the gravel.

Porosity of the top-most 15 ft of saturated zone was estimated using the lithology descriptions provided in the drillers' logs and using published values for porosity for various rock types (Domenico and Schwartz, 1990). Domenico and Schwartz publish a range of typical porosity values for each rock type. For each rock type described in the drillers' logs for the study area, we used the mid-point of the range published in Domenico and Schwartz. For rock types not listed by Domenico and Schwartz, a similar rock type was used. For lithology descriptions of a mix of rock types (for example 'sand and clay'), an average was taken of the porosities of the individual rock types. Table 2 shows a list of the rock types described in the drillers' logs for the water-bearing strata and the average porosity values used in this study.

In some wells, two or three saturated zones in the same well were used to make up 15 ft of saturated thickness. For example, the top-most zone might have had a saturated thickness of only 10 ft, in which case, the saturated thickness of the next zone was also considered in assessing the hydrologic parameters of the top 15 ft of saturated zone. When more than one zone was used to evaluate porosity, a weighted average based on the contributing thickness of the water-bearing zone was used. For example, if the top zone was 10 ft of sand and the second zone was 20 ft of gravel, the top saturated 15 ft was considered to be 10 ft of sand and 5 ft of gravel and the porosity values for sand and gravel were weighted $\frac{2}{3}$ and $\frac{1}{3}$ respectively.

Porosity estimates for the individual wells were interpolated using kriging in ESRI Arc-Map 9.0. Figure 7 shows a map of the estimated porosity distribution for the study area.

Study Area Recharge

As assessment of recharge to the study area was outside the scope of the project. Petrich and Urban (2004) analyzed recharge in this area for the Treasure Valley Study, so the reader is referred to that work.

Hydrologic Characteristic Summary

Figures 3 through 7 present a summary of the hydrologic characteristics for the study area. The reader is again cautioned that these figures are based on data from the drillers' logs and from published average values. Figures 3 through 7 provide a guideline for parameters used in an N-P Level 1 assessment. As more hydrologic data becomes available in the study area, these figures should be updated and refined.

Water Quality Investigation

Introduction

Water quality in Canyon County was investigated to determine if problems exist due to elevated concentrations of arsenic, radionuclides (in particular uranium), nitrate, and thermal waters. The introduction of onsite wastewater systems in subdivisions, as development spreads across the county, and impacts due to agricultural loading are the primary causes for concern for nitrate. The uranium concerns are due to the introduction of new EPA limits on uranium in community drinking water systems. Previous water quality sampling has shown apparently localized areas with high levels of uranium in the ground water in Canyon County. An ultimate goal of IDEQ is to identify specific water-bearing strata which are characteristically high in uranium concentration, to provide well construction guidelines which would avoid these strata.

Uranium has become an important regulated drinking water contaminant of concern due to the increased understanding of its chemical (kidney toxicity) and radioactivity (carcinogenic potential) properties (ATSDR, 1999). In December 2003, the USEPA published updated guidelines setting the MCLG for radionuclides, uranium and daughter products of U-236 and Th-232 (gross alpha, combined radium 226/228, and uranium) at zero and, in addition, set a new MCL for uranium at 30 µg/L for community water systems (USEPA, 2003).

The weathering of granites (uranium concentrations typically ranging from 2.2-6.1 ppm), and the application of phosphate fertilizer (uranium concentrations typically ranging from 50 to 200 ppm) have been linked to increased uranium concentrations in the subsurface (Langmuir, 1997; Zielinski et al., 2006 and 1995; Guzmán, 2002, 2006; Gascoyne, 1982). As uranium is released into the saturated zone, its mobility, reactivity, and solubility are dependent upon oxidation state (+4, +6), pH, and carbonate complexation. In reducing waters, uranium concentration is typically less than 0.01 ppb as U(IV), and in oxidizing waters, the uranium concentration is typically in the range of 0.1 to 100 ppb as U(VI) (Langmuir, 1997). The solubility of U(VI) can be increased by the formation of fluoride, phosphate, and carbonate complexes (Langmuir, 1978), increasing its mobility. Uranium can be immobilized in clay layers by adsorption to iron oxides and oxy-hydroxides (Taboada, 2006; Porecelli, 2003); however, in the presence of carbonates, the uranium preferably complexes with the carbonates, leaving the uranium in solution and inhibiting the adsorption to the iron hydroxides (His, 1985). Immobility of uranium has also been observed in regions where the subsurface transitions from oxidizing to reducing conditions, reducing the U(VI) to U(IV) and immobilizing U(IV), as seen in the formation of uranium roll fronts (Langen, 1974). Predicting the location of uranium within certain water-bearing zones will be dependent on pH, redox, carbonate complexation, and source of uranium.

Our objectives in the water quality component of this study were to determine whether uranium was a contaminant of concern within Canyon County, and if it is a concern whether the occurrence of uranium can be isolated to a specific water-bearing zone or source. To fully characterize the source of uranium, a comprehensive analysis, including

lithology, different water chemistry signatures between areas of high, medium, and low uranium concentrations, and observed correlations between uranium and other redox-sensitive elements or other inorganic constituents is needed. Additionally, we were investigating whether other potential drinking water contaminants (nitrate and arsenic) and thermal waters are a concern for the study area.

Existing Data

Analysis of Well Drill Cuttings

The USGS conducted a study in southwestern Idaho (USGS, date unknown) investigating arsenic concentrations in drill cuttings collected from 7 wells. The USGS was investigating the possible geologic sources of arsenic in the hydrologic environment. In addition to arsenic, the drill cuttings were analyzed for uranium and other trace metals. The highest observed concentrations of uranium (greater than 4ppm, Table 3) were in clay layers and the lowest observed uranium concentrations (less than 1ppm, Table 4) were observed in sand layers. Table 5 lists published typical uranium concentrations for granites and oceanic sands and clays (Gascoyne, 1982). The highest concentrations of uranium published in the USGS report (Table 3) are just above the published typical concentrations.

Existing Water Quality Data

Existing water quality data were used to provide insight into the regional water quality in the study area and to help guide selection of the wells to be sampled. Data were collected from the on-line water quality inventory (USGS, 2006a) and from the IDEQ Safe Drinking Water Information System (SDWIS) data base, (IDEQ, 2006). Figure 8 shows the location of wells with existing water quality data. The wells in the data base were correlated with the existing water quality data (discussed below) and the water quality data were linked into the data base.

Existing water chemistry data collected from the USGS do not contain uranium analyses and most of the records contain water chemistry for specific contaminants without a complete water chemistry analysis (alkalinity, pH, temperature, and major cations and anions) for each well sampled. The SDWIS data contain analyses for a few regulated contaminants and represent water quality samples from community water systems (systems that service 15 connections or serve 25 or more persons year-round).

Specific conductance, a good indicator of total dissolved solids, was mapped spatially for the study area using the kriging function in ESRI Arc-Map 9.0 (Figure 9). High specific conductance indicates more total dissolved solids, and low specific conductance indicates fewer total dissolved solids. Figure 9 shows an area of low specific conductance near the river, northeast of Caldwell, ranging well into T4N R2W. This could be due to dilution from either river seepage or from seepage incidental to agricultural irrigation. This variation in specific conductance could also be the result of sampling of different localized aquifers with varying water chemistry.

Gross alpha, arsenic, uranium and nitrate levels recorded in the SDWIS and USGS data bases were also spatially mapped using ESRI Arc-Map 9.0. Figure 10 shows the gross alpha measured in the study area, in picoCuries/Liter (pCi/L). Areas of high gross alpha in Figure 10 correlate with areas of high specific conductance in Figure 9. However, far fewer wells have been analyzed for gross alpha, so it is difficult to draw many conclusions from the data. Figure 11 shows the spatial distribution of arsenic in the region. Some areas of elevated arsenic are seen northwest of Middleton, in T5N R3W and west and southwest of Caldwell, both inside and outside the study area.

Very few wells in the region have been previously analyzed for uranium. Figure 12 shows the spatial distribution of uranium near the study area. Elevated uranium levels have been observed in T5N R3W. Additionally, elevated uranium levels have been observed northeast of Nampa, east of Lake Lowell and northwest of Lake Lowell. Figure 13 shows nitrate levels throughout the study area, which shows much the same pattern as the other constituents.

Figures 9 through 13 all show a possible arc of lower water quality starting in T5N R3W, ranging south through Caldwell, including the Lake Lowell area and east through Nampa. This observed trend might be real, or it may be a relic of the location of previously sampled wells (Figure 8). As with specific conductance, gross alpha, arsenic, uranium and nitrate may have been sampled from wells completed in localized aquifers at different depths, so the reader is cautioned in drawing conclusions from Figures 9 through 13.

Sampling and Analysis

Willow Creek Gravel Digestions

One of the hypotheses stated by Otto (2005) is that the Willow Creek gravels are the source of the radionuclides in the ground water in the study area. There is one known outcrop of the Willow Creek gravels (Figure 3 in Otto, 2005) in the region surrounding the study area. To test this hypothesis, samples from this outcrop were collected and analyzed for uranium and thorium.

Eight samples of Willow Creek gravels were collected from the outcrop in Canyon County (Figure 3 in Otto, 2005). The original samples were split to ensure that a complete representation of each sample was analyzed. Rock digestions of the Willow Creek gravel samples were done at the Geology Lab at Idaho State University, Pocatello, Idaho using a Lithium-Metaborate Fusion Technique, (Jarvis, 1992). The eight samples were split into two classifications: either rock or cement. The digestions were diluted using 5% nitric acid and analyzed on an Inductively Coupled Plasma-Mass Spectrometry (ICP-MS, 7500c Series Agilent Technologies, Inc., Palo Alto, CA).

Selection of Water Quality Sampling Wells

Wells for water quality sampling were selected to represent spatial and vertical variation within the study area and to reflect previous knowledge of locations that may have high and low uranium concentrations. Approximately 3000 well logs collected from IDWR

(discussed above) were evaluated to select wells for sampling. The spatial representation consists of the four townships within the study area, wells along Lake Lowell, and wells southeast of Meridian. Vertical variation was achieved by selecting wells completed at varying depths (shallow < 150ft and deep > 150ft) with differing lithologies (clay, sand, and gravel). The elevation of the water-bearing zones (screened interval or bottom of casing to the bottom of an open hole) were estimated using land surface elevation from USGS 10 m DEMs (USGS, 2006b) and subtracting depth to the water-bearing zone. The wells were categorized regionally as deep and shallow, as follows:

- Deep Wells < 2267ft above sea level
- Shallow Wells 2267-2435 ft above sea level

The preexisting water chemistry and radionuclide data collected from the USGS and SDWIS for approximately 215 wells were used in selecting wells with previous high and low uranium concentrations. Figure 14 shows the location of wells which were sampled for this project. In addition to the 20 wells selected specifically for the current study, the BSU collaborators selected wells outside of the study area which met their needs for their arsenic study. All wells were included in the data analysis.

The selected wells were grouped geographically into 6 clusters and then sub-grouped into shallow and deep sub-groups within each cluster. Figure 14 shows the spatial clustering and Table 6 lists the assignment of sample wells to clusters and sub-groups.

Clusters 1, 2, 3, 5 and 6 are explicitly shown on Figure 14, the balance of the wells (S5, S15, S17, S21, S23, S24, and S26) fall into Cluster 4. A description of each cluster follows.

- Cluster 1: Six wells located within approximately 1000 ft of each other, with previously high uranium concentrations, completed at varying depths.
- Cluster 2: Five wells on the border between 05N03W and 04N03W located in areas of different specific conductance (Figure 9), completed at varying depths and in different lithologies.
- Cluster 3: Two wells in close proximity, but completed at varying depths.
- Cluster 4: Seven wells that are spatially separated in all four of the townships with similar water-bearing lithologies.
- Cluster 5: Three wells along Lake Lowell completed at varying depths.
- Cluster 6: Four wells southeast of Meridian completed at varying depths.

Ground Water Sample Collection and Water Quality Analysis

Ground water samples were collected following the recommendations of the Ground Water and Soils Quality Assurance Project Plan (IDEQ, 2001). A YSI 556 Multi-Probe System (MPS) with flow cell was used to measure DO, pH, specific conductance, temperature, and oxidation/reduction potential (ORP) in the field. The sampled wells were purged until temperature, conductance, and pH stabilized. Due to pumping complications, sample S21, located in Caldwell, was collected without purging the well. Alkalinity was determined in the field for all samples by acid titration using a Hach Kit to

a pH endpoint of 4.6. All wells were sampled once. A blank was collected in the field for most sampling days. DI water was used for the blanks in the field. During analysis, all blanks showed non-detect levels of all constituents, indicating no contaminant issues during sampling.

Samples for major and trace inorganic ions were filtered using an inline Millipore disposable groundwater filter capsule (GWSCO4501, 0.45µm) and then collected in 60ml Nalgene bottles. Samples for major cations and trace inorganic ions were acidified to a pH < 2 with concentrated nitric acid. Samples to be analyzed for ammonium were acidified to a pH < 2 with concentrated sulfuric acid. All samples were packed on blue ice in the field and stored at 4°C in the lab until analysis.

Major cations and anions (Na, Ca, Mg, K, NH₄, F, Cl, SO₄, NO₃, PO₄) were measured using Ion Chromatography (IC, Dionex, Sunnyvale, CA), and trace inorganic ions (As, Ba, Be, Bi, Cs, Ga, Li, Rb, Se, Sr, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Tl, V, Zn, Ce, Dy, Er, Eu, Dg, Ho, La, Lu, Nd, Pr, Sc, Sm, Tb, Th, Tm, U, Y, Yb) were determined using ICP-MS (7500c Series Agilent Technologies, Inc., Palo Alto, CA). A charge balance error expressed as percentage was calculated for all samples. Seventy-five percent of the samples were within the acceptable range of less than 5% charge imbalance.

$$\text{CBE} = 100 * (\text{meq}_{\text{cations}} - \text{meq}_{\text{anions}}) / (\text{meq}_{\text{cations}} + \text{meq}_{\text{anions}}) \quad (\text{eq. 1})$$

Results

Willow Creek Gravel Digestions

Uranium concentrations in the Willow Creek gravels ranged from 1.77 to 5.24 ppm in the cement samples and 0 to 9.05 ppm in the rock samples. Thorium concentrations ranged from 6.06 to 11.59 ppm in the cement samples and 0 to 53.21 ppm in the rock samples. Table 7 lists the uranium and thorium concentrations in the analyzed Willow Creek gravels.

Water Sample Analysis

The water quality results for field measurements, major cations, anions and trace inorganic species are listed in an accompanying spreadsheet. Uranium, arsenic and nitrate concentrations are discussed below.

Uranium Results

Uranium concentrations in the 27 samples ranged from less than 1 µg/L to 83 µg/L and are shown spatially in Figure 15 and are listed in Table 8. Of the 27 wells sampled, 26% were above the MCL for uranium (30 µg/L), 37% were between 10-30 µg/L, and 37% were less than 10 µg/L. Uranium concentrations greater than 30 µg/L were observed in Clusters 1, 3, and 4. Uranium concentrations greater than 12 µg/L were observed in the shallower wells (2267-2438 ft asl) while the deeper wells (< 2267 ft asl) exhibited less than 8 µg/L uranium. Some of the shallow wells had uranium concentrations less than 12 µg/L (sample S14 in Cluster 2, S18 in Cluster 5 and wells in Cluster 6). The water-bearing zone for sample S14 was at 2276 ft asl, 10 ft shallower than the deep wells, and

the water-bearing zone for S18 was at 2323 ft, 112 ft shallower than the deep wells. The water-bearing zones for the wells in Cluster 6 ranged from 2579 to 2740, several hundred feet shallower than the regionally “deep” wells.

Piper diagrams were created for all of the water quality results. For the purpose of the piper diagrams, the uranium data was grouped into 4 classifications as follows:

- < 5 µg/L U
- Low: 5 to 10 µg/L U
- Mid: 10 to 30 µg/L U
- High: > 30 µg/L U.

Figure 16 shows the piper diagram for all wells sampled for the project. Inspection of the piper diagram shows that the high and mid uranium concentrations are located in Ca-Mg-HCO₃ waters.

Figures 17 through 22 show the piper diagrams for wells in Clusters 1 through 6, respectively, and Table 8 list the sample name, cluster, lithology, and water chemistries for the sampled wells. Correlations can be observed for depth, uranium concentrations, and water chemistries in the piper diagrams for each cluster.

The six wells in Cluster 1 were known to have high uranium concentrations from previous sampling and are spatially very close to each other, as can be seen in Figure 14. The wells are completed at different elevations; S8 and S11 are completed at an elevation of approximately 2350 ft. S9, S10, S12, and S13 are completed at elevations within about 30 ft of each other, at approximately 2300 ft. The water quality results showed that the shallower wells had uranium concentrations ranging from 15-16 µg/L, whereas the deeper wells had uranium concentrations ranging from 68-83 µg/L. Figure 17 shows the piper diagram for Cluster 1 wells. Figure 17 shows distinct water chemistry differences between the shallower wells and the deeper wells within Cluster 1. The deeper wells are completed in water-bearing zones of either sand or sand and clay. The shallower wells are completed in sand and gravel. No correlation can be drawn between lithology and uranium concentration, but there is a distinct correlation between depth and uranium concentration in Cluster 1.

The wells in Cluster 2 were selected to represent different specific conductance (Figure 9), completion depth and lithology. Figure 18 shows the piper diagram for the Cluster 2 wells. Wells with concentrations less than 5 µg/L uranium and mid-uranium concentrations had distinct water chemistries as observed in Figure 18. The wells with less than 5 µg/L uranium are located in low specific conductance areas (134-209 µS/cm) and are completed in clay or sand. The wells with mid-uranium concentrations are in higher specific conductance areas (655-785 µS/cm) completed in gravels, and are regionally “shallow” wells except for sample S14. The water-bearing zone for S14 is located at 2279 ft and the “deep” well classification is < 2267 ft; however, the water chemistry for S14 is more typical of the “shallow” wells in Cluster 2. In Cluster 2, there

was an observable correlation between mid-uranium concentration and lithology and a correlation between high specific conductance and high uranium concentration.

The two wells in Cluster 3 are in close proximity to each other and are completed at different depths. Both wells are considered “shallow” wells on a regional basis and both wells had uranium concentrations above 12 µg/L; however, the deeper well (S16) had a uranium concentration of 47.48 µg/L compared with 12.09 µg/L in well S22. Well S16 is completed in clays, while S22 is completed in gravel and sands. Figure 19 contains the piper diagram for the wells in Cluster 3. Figure 19 shows the distinct water chemistry between the deeper and shallower wells in Cluster 3.

Cluster 4 is comprised of seven wells that are spatially separated in all four of the townships and all completed in similar lithologies, but at two different elevations. Three of the wells (S21, S24 and S26) are south of the Boise River and had mid to high uranium concentrations: two of these wells had greater than 30 µg/L uranium and the third well had 24.10 µg/L uranium. These three wells are completed at elevations within 50 ft of each other. A fourth well in this cluster (S15), located north of the Boise River and northwest of Star, Idaho, is also completed within 50 ft elevation of the three wells south of the Boise River and had a concentration of uranium of 19.36 µg/L. The remaining three wells in this cluster had concentrations less than 8.33 µg/L uranium and are regionally “deep” wells. Figure 20 shows the piper diagram for the Cluster 4 wells. The piper diagram demonstrates the geochemical differences between the low uranium and mid to high uranium chemistry signatures (Figure 20). The regionally “deep” wells have lower uranium concentrations, whereas the regionally “shallow” wells have higher uranium concentrations. There was no distinct correlation between the lithology of the water-bearing zone and uranium concentration; however, there was an observable correlation between completion depth and uranium concentration.

Cluster 5 is a set of three wells along Lake Lowell which are completed at different elevations. Wells S18 and S19 are located near to each other, but are completed at elevations which are separated by approximately 100 ft, with S18 being the deeper of the two wells. The third well, S20, is located at the northwest corner of Lake Lowell and is completed at an elevation similar to S19. Wells S19 and S20 had very similar water chemistries. These two wells, on a regional basis, are completed at “shallow” depths. Of the three wells, S18, the deepest of the three wells, had the lowest uranium concentration although none of the wells had a uranium concentration higher than 16 µg/L. Figure 21 shows the piper diagram for the Cluster 5 wells. Distinct water chemistries were observed between deep and shallow wells. The deepest of the three wells, S18, is completed in sand. The other two wells, with the higher uranium concentrations, are completed in sand and gravel.

Cluster 6 is a set of four wells southeast of Meridian completed at different elevations. On a regional basis these four wells are all within our “shallow” well classification; however, they show a similar trend to the other clusters. Well S1 is completed at an elevation more than 100 ft lower than Wells S2, S4 and S6. There is a distinct water chemistry signature between the shallow three wells and the single deeper well within

this cluster. Figure 22 shows the piper diagram for Cluster 6, showing the distinct water chemistry signature between the shallower wells and the deeper well. None of these four wells had uranium concentrations higher than 12 µg/L.

There was an overall trend in the water chemistry data for all clusters. All high uranium concentrations were located in relatively shallow wells. The regionally “deep” wells consistently had uranium concentrations less than 9 µg/L. A correlation between alkalinity and uranium concentration for all the newly-sampled wells was observed. Wells with concentrations less than 85 mg/L alkalinity as CaCO₃ had less than 1.5 µg/L uranium, while the wells in the study area with alkalinity as CaCO₃ concentrations above 211 mg/L had greater than 30 µg/L uranium. Log (U_{ppb}) was plotted against alkalinity and is shown in Figure 23. The linear relationship between log (U_{ppb}) and alkalinity had an R² = 0.75, as shown in Figure 23.

Log (U_{ppb}) was also plotted against specific conductance, nickel, magnesium, calcium, strontium and nitrate (Figures 24 through 29 and Table 9). Strong linear relationships between log (U_{ppb}) and specific conductance, nickel, magnesium, strontium, and calcium were observed. There was less of a correlation between uranium concentration and nitrate (R²=0.456, P-value 0.00012).

Arsenic Results

Arsenic concentrations analyzed in this study ranged from 1.5 to 114 µg/L. Five samples were above the MCL (10 µg/L). Two wells near Lake Lowell (S19 and S20) in Cluster 5 had very high arsenic concentrations at 49 µg/L and 114 µg/L, respectively, and three wells (S4, S8, S11) were just above 10 µg/L. Figure 30 shows the arsenic results for the 27 wells. Out of the 27 samples, 19% were above the MCLs (10 µg/L), 22% were between 5-10 µg/L, and 59% were below 5 µg/L.

Nitrate Results

Nitrate concentrations ranged from less than 1 mg/L to 15.08 mg/L nitrate as N. Two wells within the study, S10 and S24 (Figure 31), were above the MCL (10 mg/L). Of the 27 wells sampled, 7% were above the MCL (10 mg/L), 26% were between 5 and 10 mg/L, and 67% were below 5 mg/L of nitrate as N.

Thermal Water Results

No thermal water was observed from the 27 wells sampled. The average ground water temperature was 15.53°C +/-1.78°C. The temperature range observed in the 27 wells was 13.42-21.16°C.

Oxidizing versus Reducing Environment

One sample out of the 27 samples collected appeared to have characteristics indicating a reducing environment. Well S29, northwest of Middleton in Cluster 2, had less than 1 mg/L D.O., negative ORP, 0.06 mg/L NO₃ as N, 4.51 mg/L SO₄, and 0.75 µg/L U (Table 8). Recall that in reducing environments, uranium is in the +4 oxidation state and is immobilized.

Discussion and Conclusions

The uranium concentrations in the Willow Creek Gravel digestion did not show any indication of being a source of high uranium. Comparison of Table 7 with the typical published ranges for uranium and thorium concentrations (Table 5) show that the uranium and thorium concentrations in the Willow Creek gravels were not unusually high. The ratio of Th/U was also within the published range for gravels. Arsenic research indicates that repetitive wetting and drying cycles in the vadose zone can leach enough arsenic into the ground water to cause a contamination problem, even when the arsenic concentrations in the rock matrix are within normal, published values (Benner, 2006). Therefore, the Willow Creek gravels cannot be completely ruled out as the source of uranium contamination.

Sample S21 was left in the data set even though the well was not purged before sampling, due to complications in pumping. The well had been sampled in 2000 and recorded in the USGS data base. The sample collected for this study and the sample collected in 2000 had very similar water chemistries (Table 10), therefore the new data remained within the data set.

The high uranium concentrations were observed in a variety of water-bearing zones; sand, brown and blue clay and sand, sand and clay, or tan clay. None of the water-bearing zones with uranium concentrations above 30 µg/L were in gravels. No observable correlation was observed when comparing lithology to uranium concentration in the samples (Table 8). The variability in uranium concentrations within the lithology types could be due to; 1) no correlation existing between uranium and lithology, 2) inaccurate reporting of lithology in the well logs, 3) mixing between water-bearing zones, 4) the observed uranium concentrations have migrated some distance from the source rock, or 5) the observed high concentrations of uranium may be due to a point source contaminant (e.g. phosphate fertilizers).

A positive correlation was observed between $\log(U_{ppb})$ and specific conductance, alkalinity, nickel, magnesium, strontium, nitrate and calcium (Table 9 and Figures 23-29). Zielinski et al. also observed a positive correlation between uranium and specific conductance, calcium, magnesium, and strontium in surface and spring waters in Colorado (Zielinski, 1995). The high correlation between uranium and alkalinity ($R^2 = 0.749$, P-value $2.73E-9$) is an indication that carbonate complexation may play a significant role in uranium mobility in Canyon County, thus making it very difficult to predict the source of uranium within the subsurface. Alkalinity is a less costly and more common analysis than uranium analysis. High alkalinity does not indicate high uranium; however, it can be used to indicate where further sampling for uranium should occur.

Nitrate, another contaminant of concern, was positively correlated to uranium concentrations ($R^2=0.456$, P-value of 0.00012). Both nitrate and uranium can be associated with fertilizer application. There are studies investigating phosphate fertilizers as a source of uranium contamination (Guzmán, 2002, Zielinski, 1995) as well as the link between nitrate contamination and agricultural practices (Guimerá, 1998). However, these references report the elevated uranium and nitrate concentrations closer to land

surface than is observed in the wells in Canyon County. Two of the samples (S24 and S10, from Clusters 1 and 4, respectively) were above the MCLs for both nitrate and uranium. Samples with nitrate concentrations above 5 mg/L as N also had uranium concentrations above 16 µg/L. It is possible that a poorly sealed well could transmit surface contaminants from fertilizers along the annular space directly to the aquifer, which would explain the contaminants at depth.

Due to the lack of data indicating a reducing environment, a comparison between uranium concentrations in reducing versus oxidizing environments was not established in the study. However, from the 27 samples collected, the probability of uranium being immobilized in reducing environments within Canyon County is highly unlikely due to the highly oxidized environment that was encountered throughout the study area. However, if there is a zone within Canyon County that was once reducing, but now has oxidizing water, the uranium can be released due to weathering processes within the subsurface, causing an increase in uranium concentration in the aquifer.

Water chemistry data from each cluster exhibited a distinct trend between shallow and deep wells. The piper diagrams demonstrate distinct water chemistries, including high and low uranium concentrations, versus depth within each cluster. The high to mid uranium concentrations were in the shallower wells. This is a point of concern in the region since most domestic wells are completed in shallow water-bearing zones.

The wells in Cluster 1 are particularly useful because they represent six wells very close together, completed at differing depths and exhibiting different levels of uranium contamination. Figure 32 shows an aerial photo of the Cluster 1 wells. The six wells are located within the same quarter-quarter section, which is 40 acres in area and ¼ mile square. Therefore, the maximum distance between any two wells in Cluster 1 is approximately 1,000 ft. Figure 33 shows the lithology and elevations of the Cluster 1 wells. Within Cluster 1, wells S9, S10, S12 and S13 all had high concentrations of uranium. All four of these wells are completed at elevations ranging between 2250 and 2300 ft asl, providing strong evidence of a correlation between completion depth and uranium concentration, in the vicinity of the Cluster 1 wells.

Although relatively few wells were sampled for this pilot study (27 wells), 26% exhibited uranium concentrations above the MCL for private drinking water wells. The wells which had high uranium concentrations were distributed throughout the four sections of the study area. It is reasonable to conclude that there is a concern for uranium in the drinking water supply within the study area.

Recommendations for Future Work

Further water quality analysis of spatially and vertically distributed wells within Canyon County is required to make any further conclusions concerning the water-bearing zones with high uranium concentrations. Further investigation is also needed to investigate possible sources of the uranium contamination including a) the potential linkage between phosphate fertilizer and uranium concentrations in the aquifer and b) the potential for the

uranium to be leached out of the vadose zone through cycles of wetting and drying. These three potential avenues of investigation are discussed below.

Further Investigation of Spatial and Vertical Distribution of Uranium

Using the results of the pilot project, we recommend further investigation of the water quality in the Canyon County area. The extent of the area and the vast number of wells makes it difficult to recommend a specific approach. One potential approach would be to concentrate efforts in the vicinity of the Fairway Estates subdivision, which seems to exhibit consistently high levels of uranium in the ground water. Looking at Figure 33, it may be fruitful to search for wells in the vicinity of Fairway Estates which are completed at elevations between 2250 and 2300 ft asl. Wells S10, S12 and S13, all located at Fairways Estates, exhibit high uranium concentrations, are completed between 2250 and 2300 ft asl and have coarse sand at or near the screen or the bottom of the well. Well S9 is completed at approximately 2300 ft asl, but did not have coarse sand near the screen. These wells would indicate that investigation of wells in the vicinity of Fairway Estates completed at similar elevations and completed in or near coarse sands may yield more information about the areal extent of the uranium contamination. A closer look at oxidizing and reducing conditions in the region is probably also warranted, due to the relationship between uranium solubility and oxidizing/reducing conditions.

Investigation of Linkage Between Land Use and Uranium Contamination

In order to investigate the possible linkage between land application of fertilizer and uranium contamination, we recommend the following steps.

1. Again, concentrate efforts in the vicinity of the Fairway Estates subdivision, which appears to have consistently high uranium concentration levels
2. Investigate the potential for the annular space around the outside of a well to be transmitting contaminants from land surface to the aquifer by using a conservative tracer. This would entail saturating the land area around the well with clean water, adding water with a conservative tracer such as bromide, and then sampling the well for occurrence of the tracer. A positive occurrence of the tracer would demonstrate a linkage. Inability to detect the tracer would be less conclusive.
3. Conduct a mass balance of the uranium concentrations in the fertilizer versus the concentrations detected in the aquifer to determine whether it is possible for the fertilizer to yield uranium concentrations experienced in the aquifer.
4. Analyze fertilizers commonly used at the land surface for uranium concentrations. Compare isotope ratios of the uranium in the fertilizers with isotope ratios in the contaminated aquifer to determine whether the fertilizer is a potential source.

Investigation of Vadose Zone Leaching

The similarity in geochemical transport behavior between uranium and arsenic, and the occurrence of both contaminants in the Canyon County region, may make it beneficial to study both constituents simultaneously. We recommend follow-up work to explore the potential for the wetting and drying cycles of the vadose zone contributing to the uranium (and arsenic) concentrations in Canyon County. Possible investigation steps might include the following.

1. Locate new wells being drilled using rotary air drilling rigs. Contract with the well drillers to pull cuttings during the drilling process. Ideally, cuttings should be obtained from wells being drilled in the vicinity of wells with known arsenic or uranium contamination.
2. Conduct leaching tests on some of the cuttings in the laboratory to leach out arsenic and uranium from the cuttings. Idealized leaching tests should show whether the arsenic and uranium concentrations in the cuttings could support arsenic and uranium concentration levels measured in the ground water.
3. Conduct rock digestions on the balance of the cuttings to analyze concentrations of arsenic and uranium in the rock cuttings.
4. Analyze local hydrology to investigate whether there are sufficient seasonal changes in aquifer water levels to support the theory that successive wetting/drying of the vadose zone is leaching out the contaminants.
5. Conduct a mass balance calculation to support or refute the theory.

References

- Agency for Toxic Substances and Disease Registry (ATSDR). 1999. ToxFAQs™ for uranium. www.atsdr.cdc./facts150.html.
- Benner, S., 2006. Personal communication.
- Domenico P.A. and F.W. Schwartz, 1990. Physical and Chemical Hydrogeology, John Wiley & Sons, U.S.A.
- Gascoyne, M., 1982. Geochemistry of the actinides and their daughters, In: M. Ivanovich and R.S. Harmon (Editors), Uranium series disequilibrium: application to environmental problems, Clarendon Press-Oxford. pp33-55.
- Guimerá, J., 1998. Anomalously high nitrate concentrations in ground water, *Ground Water*, Vol. 36 (2), pp. 275-282.
- Guzmán, E.T.R.; M.V.E. Alberich, E.O. Regil, 2002. Uranium and phosphate behavior in the vadose zone of a fertilized corn field, *Journal of Radioanalytical and Nuclear Chemistry*. Vol. 254 (3), pp. 509-517.
- Guzmán, E.T.R, E.O. Regil, L.R. R. Gutiérrez, M.V.E. Alberich, A.R. Hernández, and E.O. Regil, 2006. Contamination of corn growing areas due to intensive fertilization in high plane of Mexico. *Water, Air, and Soil Pollution*. Vol 175:77-98.
- His, C.D. and D. Langmuir, 1985. Adsorption of uranyl onto ferric oxyhydroxides: Application of the surface complexation site-binding model, *Geochimica et Cosmochimica Acta*. Vol. 49, pp. 1931-1941.
- Hutchings, J. and C.R. Petrich, 2002. Ground water recharge and flow in the regional Treasure Valley aquifer system geochemistry and isotope study: University of Idaho, Idaho Water Resources Research Institute Technical Report IWRRI-2002-08, Boise, Idaho.
- Howarth, R., B. Burnell and B. Wicherski, 2002. Nutrient-pathogen evaluation program for on-site wastewater treatment systems, Idaho Department of Environmental Quality in coordination with Central District Health Department, Boise, ID, 26 p.
- Idaho Department of Environmental Quality, 2001. Ground Water and Soils Quality Assurance Project Plan, Boise, Idaho.
- Idaho Department of Environmental Quality, 2006. IDEQ Safe Drinking Water Information System Data Base

Idaho Department of Water Resources, 2006. On-line repository of well driller's logs.
<http://www.idwr.idaho.gov>

Jarvis, K.E., A.L. Gray, and R.S. Houk, 1992. Handbook of Inductively Coupled Plasma, Blackie, London. pp. 196-200.

Langen, R.E. and A.L. Kidwell, 1974, Geology and geochemistry of the Highland Uranium Deposit, Converse County, Wyoming. *The Mountain Geologist*. Vol.11 (2), pp. 85-93.

Langmuir, D. 1978. Uranium solution-mineral equilibria at low temperatures with applications to sedimentary ore deposits. *Geochimica et Cosmochimica*. Vol. 42 pp.547-569.

Langmuir, D. 1997. *Aqueous Environmental Geochemistry*. New Jersey. Prentice Hall.

Neace, T., 2006. Personal communication.

Otto, B.R, 2005. Preliminary geology of the northwestern portion of Canyon county, Idaho, University of Idaho, Idaho Water Resources Research Institute Technical Report 200510, Boise, ID, 21 p.

Otto, B.R., A.H. Wylie, and M.J. Martin, 2003. Hydrogeology of confined, Idaho group-hosted aquifers and overlying gravels near Greenleaf, Canyon County, Idaho. University of Idaho, Idaho Water Resources Research Institute, Boise, Idaho. Report available at: http://www.webs.uidaho.edu/gwemo/region_pages/southwest/sw_sites/greenleaf.htm.

Petrich, C. R. and S. M. Urban, 2004. Characterization of ground water flow in the lower Boise River basin, University of Idaho, Idaho Water Resources Research Institute, Technical report IWRRI-204-01, Boise, Idaho.

Porecelli, D., P.W. Swarzenski. 2003. The behavior of U- and Th-series nuclides in groundwater. In. Bourdon, B., G.M. Henderson, C.C. Lundstrom, S.P. Turner, editors. Uranium-series geochemistry, 52. *Reviews in mineralogy and geochemistry*. pp.317-361.

Taboada, T., A.M. Cortizas, C. García, E. García-Rodeja. 2006. Uranium and thorium in weathering and pedogenetic profiles developed on granitic rocks from NW Spain. *Science of the Total Environment*. Vol. 356, pp.192-206.

U.S. Environmental Protection Agency, 2006. <http://www.epa.gov/safewater/mcl.html>

U. S. Environmental Protection Agency, 2003. Part II, Environmental Protection Agency, 40CFR Part 9, 141, and 142, National Primary Drinking Water Regulations, Radionuclides Final Rules.

U. S. Geological Survey, no date available. Geochemical and Descriptive Data for Sedimentary Aquifer Materials in Southwestern Idaho, U.S. Geological Survey web publication, available at: <http://id.water.usgs.gov/projects/mdarsenic/index.html>.

U. S. Geological Survey, 2006a. USGS water quality web site <http://waterdata.usgs.gov>

U. S. Geological Survey, 2006b. USGS digital elevation map web site:
<http://seamless.usgs.gov/website/seamless/viewer.php>

Wylie, A. H., 2004. Estimating wellhead elevation, Eastern Snake Plain Aquifer Model design document DDM-011, University of Idaho, Idaho Water Resources Research Institute, Technical Report 004-021, Boise, Idaho.

Zielinski, R.A., S. Asher-Bolinder, A.L. Meier, 1995. Uraniferous waters of the Arkansas River valley, Colorado, U.S.A.: A function of geology and land use, Applied Geochemistry, Vol 10, pp. 133-144.

Zielinski, R.A., W.H. Orem, K.R. Simmons, P.J. Bohlen, 2006. Fertilizer-derived uranium and sulfur in rangeland soil and runoff: A case study in central Florida. Water, Air, and Soil Pollution. Vol 176, pp.163-183.

Contaminant	MCLG mg/L	MCL mg/L
Uranium	0	0.030
Arsenic	0	0.010
Barium	2.0	2.0
Beryllium	0.004	0.004
Cadmium	0.005	0.005
Chromium	0.1	0.1
Copper	1.3	1.3
Fluoride	4.0	4.0
Lead	0	0.015
Nitrate as N	10	10
Selenium	0.050	0.050
Thallium	0.0005	0.002

Table 1. Maximum contaminant level goals (MCLG) and maximum concentration levels (MCL) specified by the USEPA (USEPA web site).

Media	Porosity %	
Cemented Gravel	17	used sandstone values
Chert	5	used shale values
Clay	47	
Clay and Gravel	36	averaged clay and gravel values
Clay and Sand	44	averaged clay and fine sand values
Coarse Sand	39	
Fine Sand	40	
Gravel	24	
Gravel and Boulders	36	
Gravel and Sand	32	averaged gravel and coarse sand values
Hardpan	31	used siltstone values
Loam	60	estimated
Medium Sand	40	used average of coarse and fine sands
Sand	40	used average of coarse and fine sands
Sand and Silt	26	used low value for fine sand
Sand and Shale	22	used average of sand and shale values
Sandstone	18	

Table 2. Estimates of porosity used for this study.

Field Number	U (ppm)	Brief Description
DH99-4 150-160	4.29	Gray clay
DH99-4 160-170	4.16	Gray Clay
DH99-4 170-180	6.62	Dark Gray Streaky Clay
DH99-4 180-190	4.02	Gray/brown streaky clay
EM9 84-89	5.37	Streaky brown and gray clay
LN190-196	5.56	Brown Clay
WCE 125-130	4.98	Buff Clay
WCE 175-180	4.78	Brownish Gray Clay
WCE 245-250	7.85	Dark Gray Clay
WCE 424-426	5.02	Buff Clay
WCE 88-90	4.30	Tan Clay

Table 3. High uranium concentrations (greater than 4ppm) in drill cuttings collected at different depths and from different sites in Southwestern Idaho (USGS, date unknown).

Field Number	U (ppm)	Brief Description
COV 440-445	0.61	gray sand
COV 470-475	0.64	gray sand
EM9 101-108	0.59	Brownish sand
EM9 122-124	0.49	Gray medium sand
EM9 248-253	0.49	Light tan sand
EM9 334-340	0.41	Medium grayish-brown sand
EM9 44-49	0.27	Clean coarse qz-rich sand
EM9 74-79	0.44	Medium grayish-brown sand
KU6 315-320	0.89	brown, fine, uniform sand
LN 245-250	0.93	Coarse grayish-brown sand
LN170-175	0.52	Medium brownish sand
LN185-190	0.83	Coarse orange sand
LN205-210	0.84	medium pebbly sand
LN210-215	0.88	medium brown sand
LN219-225	0.70	medium-coarse orange pebbly sand
MERT 375-380	0.89	Coarse brown sand
MERT 505-510	0.98	Brownish-gray sand
MERT 570-575	0.91	medium brown sand
PS 267-272	0.57	coarse sand
PS 290-295	0.54	coarse gray sand
PS 347-349	0.49	medium-to coarse brown sand
WCE 27-30	0.69	medium brown sand
WCE 30-35	0.55	Coarse brown sand
WCE 35-40	0.58	medium brown sand
LN40-60	0.47	Dark gray basalt

Table 4. Low uranium concentrations (less than 1ppm) in drill cuttings collected at different depths and from different sites in Southwestern Idaho (USGS, date unknown).

Name	U (ppm)	Th (ppm)	Th/U
Granites	2.2-6.1	8-33	3.5-6.3
Oceanic sands and clays	0.7-4	1-30	0.4-10

Table 5. Published ranges for concentrations of uranium, thorium and the ratio of thorium to uranium in granites and oceanic sands and clays (after Gascoyne, 1982).

Cluster	Sub-group a (deep)	Sub-group b (shallow)
Cluster 1	S10, S12, S13, S9	S11, S8
Cluster 2	S14, S25, S29	S27, S28
Cluster 3	S16	S22
Cluster 4	S5, S17, S23	S15, S21, S24, S26
Cluster 5	S18	S19, S20
Cluster 6	S1	S2, S4, S6

Table 6. Newly sampled wells assigned to spatial clusters and sub-groups a and b representing deep and shallow wells within each cluster.

Samples	Uranium ppm	Thorium ppm	Th/U
1-1R	< 1ppm	< 1ppm	
2-1R	2.09	5.11	2.44
2-2R	6.54	13.39	2.05
3-1R	9.05	20.23	2.24
3-2R	6.81	53.21	7.81
4-3C	5.24	6.06	1.16
4-2R	6.98	22.32	3.20
4-1R	3.93	15.56	3.96
5-1R	3.2	9.99	3.12
5-2R	3.27	10.44	3.19
6-1R	5.14	22.78	4.43
6-2R	2.43	10.01	4.12
6-3R	3.21	9.26	2.88
7-1R	< 1ppm	< 1ppm	
7-2R	6.04	28.01	4.64
7-3C	2.69	11.59	4.31
8-1R	2.16	9.67	4.48
8-2C	1.77	7.23	4.08

Table 7. Analyzed uranium and thorium levels in digested Willow Creek gravel and cement samples. Sample names are indicated by two numbers and a letter. The first number represents the original sample, second number is the sub-sample of the original sample, and the letter indicates whether it is a R (rock) or C (cement) sample.

Sample	Cluster	Lithology	Water bearing zone	Uranium µg/L	Arsenic µg/L	Nitrate as N mg/L	Specific conductivity µS/cm	Alkalinity mg/L CaCO ₃	Reducing conditions
S1	6	Sand/gravel	2579	11.49	1.58	3.22	505	92.00	No
S2	6	Sand/gravel/clay	2656	0.61	6.79	< 1	121	53.80	No
S4	6	Clay/sand	2670	< 0.5	10.60	< 1	112	56.60	No
S5	4	Sand	2201	5.65	< 1	2.30	441	170	No
S6	6	sand	2746	< 0.5	1.54	< 1	88	39.10	No
S8	1	Sand/gravel	2352	15.80	11.04	7.54	793	282.00	No
S9	1	Sand	2308	82.66	3.21	5.14	916	258.00	No
S10	1	Sand	2278	67.66	4.16	15.08	933	211.00	No
S11	1	Sand/gravel	2350	16.30	10.31	8.41	821	276.00	No
S12	1	Brown & blue clay/sand	2278	70.94	5.01	4.18	907	248.00	No
S13	1	Sand/clay	2295	83.18	3.34	4.81	908	322.00	No
S14	2	Tan clay	2279	1.02	2.70	< 1	157	65.50	No
S15	4	Brown clay	2322	19.36	2.85	2.61	556	267.00	No
S16	3	Tan clay	2356	47.48	3.82	8.40	763	317.60	No
S17	4	Sand	2239	8.33	9.42	1.62	420	129.20	No
S18	5	Sand	2323	7.61	9.87	1.40	466	212.80	No
S19	5	Sand/gravel	2405	12.64	48.93	< 1	688	281.40	No
S20	5	Sand/gravel	2431	15.26	114.00	1.84	676	178.20	No
S21	4	Sand	2333	37.51	6.62	7.29	931	405.60	No
S22	3	Gravel/sand	2400	12.09	3.03	2.26	518	153.40	No
S23	4	Clay/sand	2260	2.97	4.13	1.36	308	105.40	No
S24	4	Clay/sand	2368	42.30	1.54	14.87	851	236.00	No
S25	2	sand	2261	1.20	2.67	< 1	209	82.00	No
S26	4	Sand	2276	24.10	2.63	1.90	725	174.60	No
S27	2	gravel	2434	16.59	7.44	7.06	785	298.20	No
S28	2	gravel	2380	15.96	4.86	5.05	655	260.00	No
S29	2	sand	2182	0.75	4.99	< 1	134	60.00	Yes

Table 8. Sample name, cluster, lithology, depth to water bearing zone, uranium, arsenic, specific conductivity, alkalinity, and reducing conditions for all sampled wells. The MCL for uranium is 30 µg/L, arsenic is 10 µg/L, and nitrate as N is 10 mg/L.

Constituents	R² Values
Specific Conductivity	0.9384
Alkalinity	0.7494
Nickel	0.7732
Magnesium	0.7823
Strontium	0.6946
Calcium	0.8326

Table 9. R-squared values for log uranium versus varying constituents from samples collected in Canyon County.

Constituents Measured	USGS (2006a) (sample collected 2000)	IWRRI (Sample collected 2006)
Temperature (°C)	15.6	21.16
Specific Conductance (µS/cm)	999	931
Dissolved Oxygen (mg/L)	6.2	4.45
pH	7.4	7.32
Alkalinity (mg/L CaCO ₃)	425	405.60
Calcium (mg/L)	71.4	65.86
Magnesium (mg/L)	26.1	20.48
Sodium (mg/L)	116	98.66
Potassium (mg/L)	3.55	2.65
Chloride (mg/L)	15.5	15.89
Sulfate (mg/L)	64.6	56.48
Fluoride (mg/L)	0.8	0.73
Arsenic (ug/L)	6	6.62

Table 10. Water chemistry analysis for sample S21 from the USGS in 2000 and IWRRI

(Excel file): Water chemistry data from newly sampled wells.

(Excel file): Trace metal water chemistry data from newly sampled wells.