

**Isotopic and Geochemical Investigation into the
Source of Elevated Uranium Concentrations in the
Treasure Valley Aquifer, Idaho**

Submitted to:

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1 Executive Summary

This study was initiated to evaluate the potential source of elevated uranium in the groundwater underlying the Treasure Valley in southwest Idaho. Groundwater in the area exhibits widespread but diffusely distributed uranium concentrations up to $110 \mu\text{g L}^{-1}$, well in excess of the U.S. Environmental Protection Agency (EPA) drinking water standard of $30 \mu\text{g L}^{-1}$. The elevated values are found in both private and public supply well waters. Data generated by field sampling (surface water, groundwater, and solid sediments) and laboratory experiments and analysis constrains the source of the observed elevated uranium concentrations. Results from surface water sampling indicate that irrigation return waters (runoff and shallow groundwater return) contain elevated dissolved uranium concentrations, suggesting that a near surface uranium source exists within the valley. When evaluated for isotopic composition, these surface waters indicate a consistent $^{234}\text{U}/^{238}\text{U}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic source signature; a signature that is also evident in the groundwater containing the most elevated uranium concentrations. To constrain the location of the uranium source, a wide variety of geologic samples, representing the stratigraphy of the Treasure Valley aquifer, were collected for bulk and leachable uranium analysis. Additionally, several phosphate fertilizers and ore samples were analyzed. The analyzed aquifer solids did not contain particularly high bulk uranium contents (avg. of 3.4 parts per million). Furthermore, isotopic analysis allowed nearly all the sampled sediments to be eliminated as potential source materials. In addition, these analyses definitively indicate that the analyzed fertilizers, as well as the phosphate rich rock used to make those fertilizers, cannot be the source of the uranium. Only one near-surface sample collected from Gowen Terrace matched the projected geochemical source signature, suggesting that discrete units in the river terrace sediments may be the source of much of the elevated uranium observed in the Treasure Valley aquifer. Elevated alkalinity values may be a useful, inexpensive indicator of waters at higher risk for elevated uranium concentrations. While this study was not able to confirm that deeper groundwater generally has lower uranium concentrations, the evidence of a near-surface source, coupled with the lack of a matching isotopic signature from deep sediments, generally supports the remedial strategy of drilling deeper wells to reach water with lower uranium concentrations. More work on further constraining potential source sediments is needed.

2 Introduction

The Treasure Valley is the largest and fastest growing, metropolitan center in the State of Idaho, and the Treasure Valley's growing population is increasingly reliant on groundwater as its primary source of drinking water. Preliminary surveys of wells across the Treasure Valley indicate the occurrence of groundwater exceeding the national primary drinking water standard of $30 \mu\text{g L}^{-1}$ uranium for public water systems established by the U.S. Environmental Protection Agency (EPA) under the Safe Drinking Water Act (Cosgrove and Taylor, 2007). Potential health effects from exposure above the standard include increased risk of cancer and kidney toxicity. Elevated concentrations of uranium (U) in this important drinking water source represent a growing regulatory concern for public water systems. It may especially pose a potential health risk to private well users, which are not regulated or required to test for uranium.

The objective of this study is to identify potential source(s) leading to elevated uranium in the Treasure Valley Aquifer, a primary drinking water source for a significant fraction of Idaho's residents. This knowledge will support decision-making by public water districts, the Idaho Department of Environmental Quality, and other federal, state, and local agencies in their efforts to manage and mediate this emerging groundwater contaminant.

2.1 Background

Cosgrove and Taylor (2007) conducted a preliminary study focusing on Treasure Valley groundwater quality within a portion of Canyon County. The study evaluated existing agency data which showed that groundwater with uranium levels in excess of the EPA drinking water standards are spatially distributed throughout the valley and often appear to exist in localized hot-spots. This study found that groundwater with high uranium concentrations was consistently characterized by Ca-Mg-HCO₃-type chemistries, and that a linear correlation exists between the log of uranium concentrations and alkalinity. Additionally, correlation was found between the log of uranium concentrations and Ca, Mg, Ni, as well as specific conductance. High uranium levels were not found in wells drawing from the deep, regional aquifer. Wells screened within shallower water bearing zones yielded higher average uranium levels. As it is believed that there is little vertical interaction between water-bearing stratigraphies at dissimilar depths (Hutchins and Petrich, 2002), groundwater with high uranium concentrations may be tied to the lithologies of specific water-bearing zones. However, no correlation was found in this study between the uranium concentrations and lithologies of the water-bearing zones.

While prior work on arsenic contamination in the Treasure Valley (Busbee et al, 2009) suggests uranium may be derived from surficial sediments, a strong trend in uranium concentrations with depth is not observed. Our ability to determine U sources or release mechanisms for the Treasure Valley Aquifer is limited by two factors:

- 1) A paucity of data on the spatial distribution of U occurrence in the aquifer.
- 2) Limited information that can be used to evaluate potential sources and processes that lead to release of uranium to the groundwater.

2.2 Project Objectives

While the observed elevated uranium concentrations in the Treasure Valley aquifer may come from a variety of sources, the spatially distributed nature of uranium occurrence suggests a source or release mechanism that is also distributed across the region. We identified three potential sources for the uranium in Treasure Valley groundwater:

- 1) Weathering of ancient lake sediments within deeper aquifer units.
- 2) Leaching of soils and sediments at the surface or within the unsaturated zone.
- 3) Application of uranium-rich phosphate fertilizers.

The objective of this research was to evaluate these three potential sources. We undertook focused tasks to reach this objective. Those tasks included:

1. Evaluation of existing groundwater data.
2. Sampling and geochemical and isotopic analysis of ground and surface waters for uranium.
3. Collection and analysis of potential solid phases, inclusive of aquifer sediments and fertilizers, as sources of uranium.

3 Methods

3.1 Existing Data Analysis

In order to initiate this research study, available geochemical data was compiled for groundwater in the Treasure Valley. Statewide Monitoring Network and Public Water System datasets were reviewed and uranium concentration data, as well as major and minor elemental compositions, were compiled. The Statewide Monitoring Network is administered by the Idaho Department of Water Resources (IDWR), and the Public Water Systems are regulated by the Idaho Department of Environmental Quality (DEQ). This combined dataset of approximately 170 groundwater wells represents the most extensive compilation and survey of groundwater uranium data for the Treasure Valley region. Utilizing GIS and graphical tools, the spatial distribution of uranium, both with respect to geographic location and depth, was assessed and geochemical trends were examined. Some inconsistencies and errors were encountered while reviewing these data. Within the public well subset, for example, uranium concentrations were inconsistently reported in units of $\mu\text{g L}^{-1}$, mg L^{-1} , and pCi L^{-1} . Because it is not typical for uranium to be reported in mg L^{-1} or

pCi L⁻¹, these discrepancies were investigated by communicating with both the DEQ and several of the analytical chemistry labs that originally produced the data. Ultimately, it was determined that the discrepancies were a relic of an erroneous data entry process effecting older data points within the public well subset. In all cases, professional judgment was used in discarding any data with suspect accuracy.

3.2 Surface and Groundwater Sampling

Informed by the findings of the existing data survey, a surface and groundwater sampling campaign was initiated in September 2009. A key component of this research was the use of uranium (²³⁴U/²³⁸U) and strontium (⁸⁷Sr/⁸⁶Sr) isotopic ratios to determine the source of the uranium found in the surface and groundwater. This isotopic method has been successfully used to differentiate sources of groundwater (Roback et al, 2001; Johnson et al, 2000) and has also proven effective at differentiating uranium derived from fertilizer and natural sources (Zielinski et al, 1997, 2000, and 2006).

Surface water samples were collected from the Boise River and its tributaries, as well as from spatially distributed locations on the Snake, Owyhee, Payette, and Weiser Rivers. Surface water samples were collected using grab sample techniques. Groundwater samples were collected by sampling both private and public water supplies. Wells sampled contained both elevated and background levels of dissolved uranium.

All samples were filtered using 0.45 µm filters and collected into acid washed bottles. Cation, anion and isotopic analysis samples were preserved using trace-grade nitric acid and stored refrigerated prior to analysis. Samples for anion analysis were stored on ice and were analyzed within 48 hours of sample collection. Isotopic analysis was performed in the Boise State University Isotopic Geology Laboratory by multi-collector thermal ionization mass spectrometry (TIMS), an approach that provides an order of magnitude greater precision than alpha spectroscopy for ²³⁴U/²³⁸U ratios and, unlike alpha spectroscopy, can also provide highly precise ⁸⁷Sr/⁸⁶Sr ratios (Schmitz and Bowring 2001). Major cations and anions, as well as trace element analysis (inclusive of U and Sr), were also analyzed using ion chromatography (IC) and inductively coupled plasma mass spectrometry (ICP-MS) utilizing the Boise State BioTrace Laboratory. Field measured parameters included pH, specific conductivity, dissolved oxygen, ORP, alkalinity, and temperature.

3.3 Solids Leaching Experiments

A solid sampling campaign was undertaken in April 2010. The goal was to evaluate potential geologic materials within the region for the capacity to release uranium, and determine which materials yield an isotopic signature similar to that observed in the Treasure Valley's elevated uranium groundwater. A suite of geologic solids were collected from a total of six locations within the region. Collection of in-situ sediments from within the aquifer was fiscally beyond the scope of this project. As an alternative approach, outcroppings representative of deeper aquifer sediments and shallow river terrace

materials were located. A range of lithologies were collected including fine-grained lake sediments, river terrace sands, loess, ash, iron-oxide coated materials, and carbonate-rich materials. Sample site locations and descriptions are found in **Appendix C**.

Solid samples were first subjected to a lithium tetra-borate assisted total dissolution procedure to measure the total uranium content of the various materials. Samples were also subjected to three individual selective leaching treatments designed to target different lithologic fractions of the solids. These treatments were developed based on a review of extraction methods present in literature (Schultz et al, 1998; Blanco et al, 2005; Dhoum and Evans, 1998; La Force and Fendorf, 2000; Martin et al, 1998; Tessier et al 1979, and Thomas et al, 1994). The selective leaching treatments were conducted in parallel on the <2 mm size fraction. An approximate 1.0 g mass of each solid sample was exposed to the leaching agents by continuously shaking the slurry solutions within sealed Teflon vessels. Subsequent to shaking, the slurries were decanted and the leachate was filtered (0.45 µm) and analyzed for both isotopic and elemental composition.

Eighteen mOhm deionized water was used to target the water soluble fraction. Thirty ml of water was added to the sample mass and the slurries were shaken at 120 rpm for 20 hours. A 1.0 M sodium acetate/acetic acid solution buffered to pH 4.5 was used to target the carbonate fraction. A 25 ml aliquot of the acetic acid solution was added to the sample mass and the slurries were shaken for 2 hours. After centrifuging at 3500 rpm for 45 min., the leachate was decanted and filtered. A second 25 ml of the acetic acid solution was added and the remaining slurries were shaken for another 2 hours. This two step process was used to ensure that carbonate-rich solids did not exhaust the acetic acid's carbonate dissolution capacity. The two batches of leachate were ultimately combined into a single volume prior to analysis. Finally, the reducible iron and manganese oxide fraction was targeted with a 0.1 M hydroxylamine hydrochloride solution brought to pH 2.0 with the addition of nitric acid. Thirty ml of hydroxylamine solution was added to the sample mass and the slurries were shaken for 5 hours.

To evaluate the hypothesis of phosphate fertilizer being a source of uranium contamination, fertilizer and phosphate ore samples were acquired. Three phosphate fertilizer samples were collected from different commercial fertilizer distributors serving the Treasure Valley. Phosphate ore rock samples were provided by a commercial operation mining the well known Phosphoria Formation in Southeastern Idaho. All fertilizer samples were dissolved in 2% nitric acid, and phosphate ores were subjected to the previously mentioned total dissolution procedure before being analyzed for isotopic and elemental composition.

4 Results

4.1 Existing Data

The data accumulated for this study, by joining public and private well data, likely represents the most extensive dataset of uranium occurrence in the Treasure Valley created to date. Among the more than 100 well locations that represent public water systems, the mean uranium concentration was 18 $\mu\text{g L}^{-1}$, the median was 12 $\mu\text{g L}^{-1}$, and the high value was 95 $\mu\text{g L}^{-1}$. Among the more than 60 private well locations with uranium data, the mean concentration was 33 $\mu\text{g L}^{-1}$, the median was 26 $\mu\text{g L}^{-1}$, and the high value was 110 $\mu\text{g L}^{-1}$ (**Table 1**). This survey indicates that groundwater exceeding the EPA standard of 30 $\mu\text{g L}^{-1}$ is present throughout the region (**Figure 1**). This suggests that the uranium source may be similarly distributed throughout the region. However there is no consistent pattern in the distribution of high uranium concentrations. Instead, several uranium hot-spots appear to be evident. Additionally, the existing data does not show any clear relationship between uranium concentration and depth, a somewhat surprising finding that may reflect uncertainties regarding the actual depth of water withdrawal due to variations in well design (**Figure 2**).

Table 1: Uranium Statistics for Public vs. Private Well Data

	Mean U $\mu\text{g L}^{-1}$	Median U $\mu\text{g L}^{-1}$	Max U $\mu\text{g L}^{-1}$
Public Wells	18	12	95
Private Wells	33	26	110

Typical range of U concentrations in groundwater affected by natural U source: 0.1 – 100 $\mu\text{g L}^{-1}$ (Langmuir, 1997. *Aqueous Environmental Geochemistry*).

Groundwater Uranium Concentrations from Public and Private Water Supply Wells

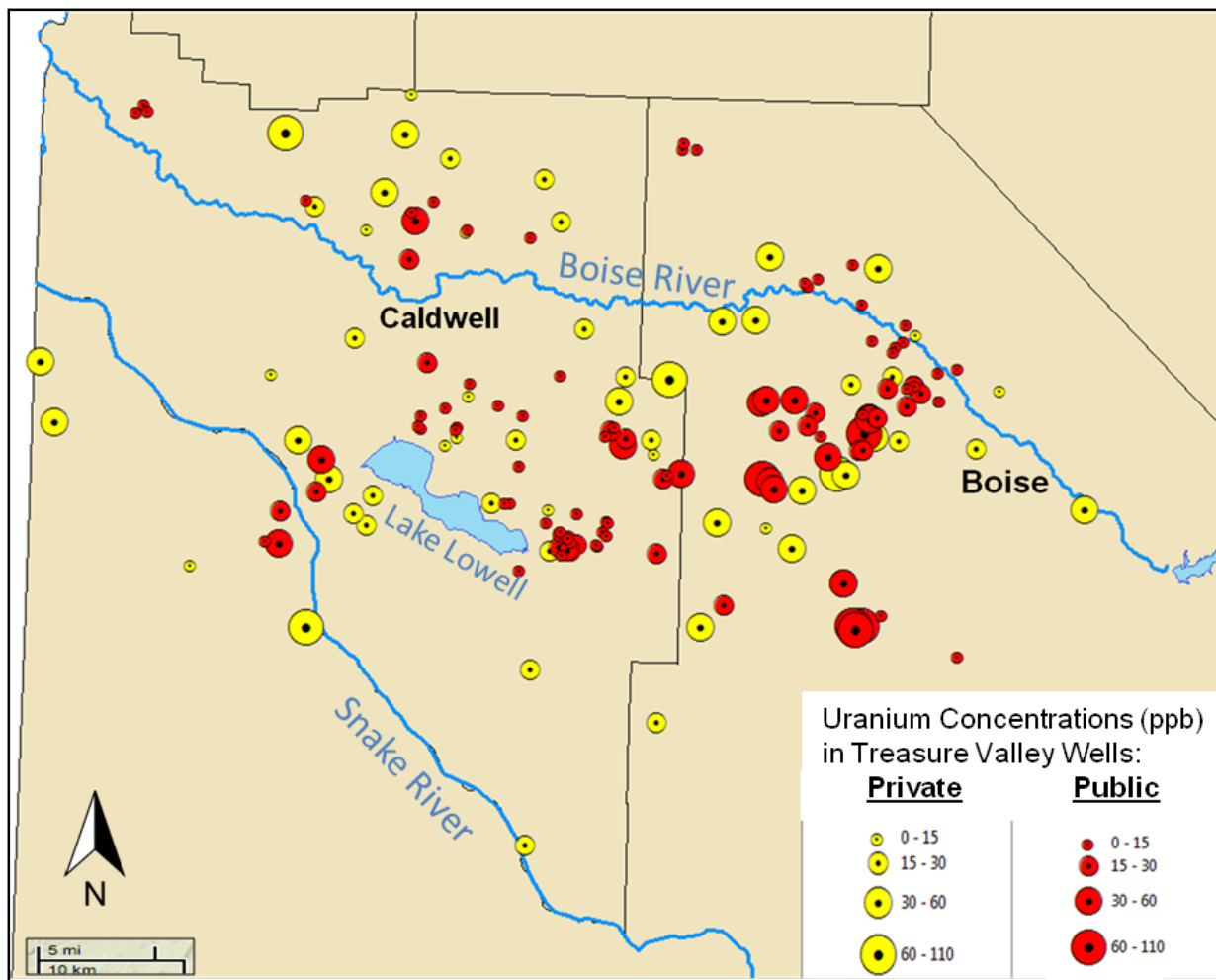


Figure 1: Groundwater uranium distribution map showing wells within the existing Public Water Systems (public) and Statewide Monitoring Network (private) dataset. Progressively larger circles indicate proportionally higher uranium concentrations in ppb notation ($\mu\text{g L}^{-1}$).

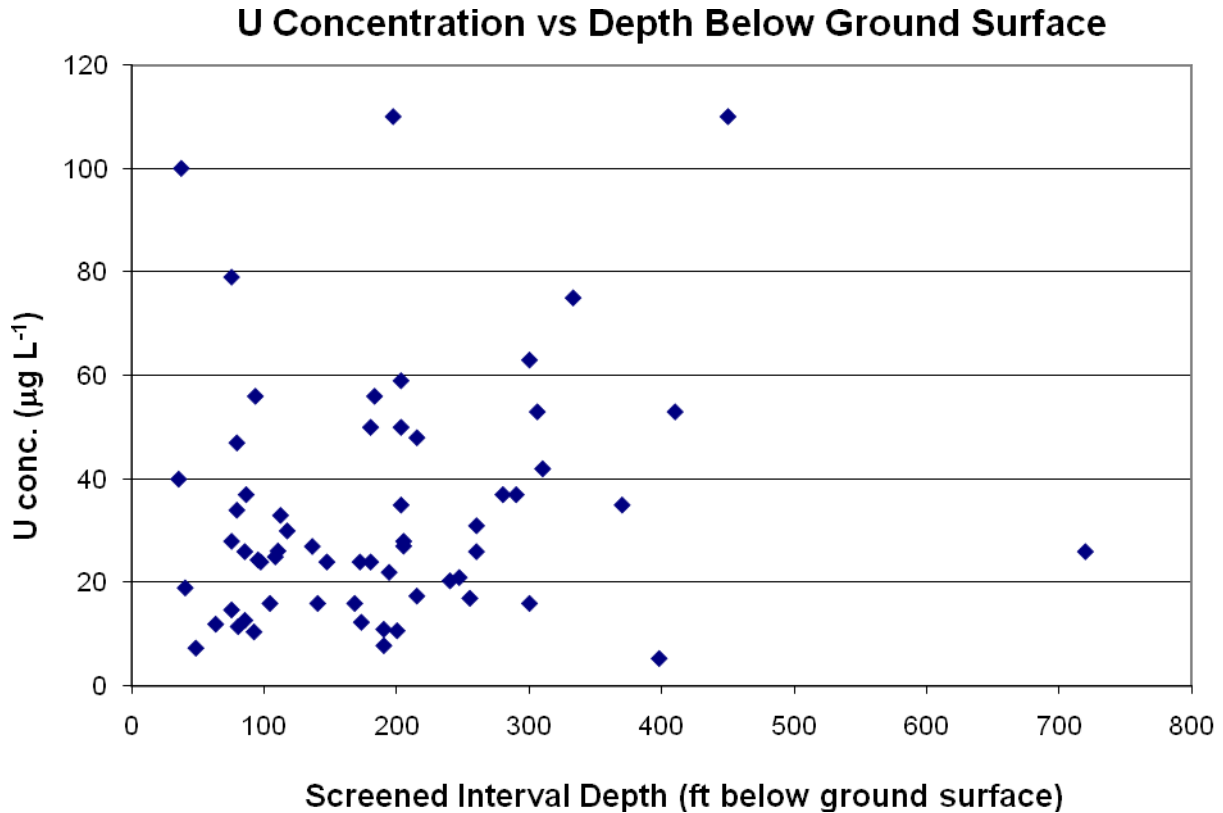


Figure 2: Groundwater uranium concentrations plotted against well depth. This plot only includes the private well portion of the existing data, as well depth information for public wells is difficult to acquire.

4.2 Surface Water

Several observations can be made from the surface water sampling results. On the Boise River, repeated seasonal sampling occurred at three locations reaching from just below Lucky Peak Dam (upstream) to just before the confluence with the Snake River (downstream). A map of the watershed locations being discussed is presented in **Figure 3**. Boise River uranium concentrations undergo an approximate 18-fold increase along this reach, from 0.3 to 5.6 $\mu\text{g L}^{-1}$ (summer) and 0.6 to 9.9 $\mu\text{g L}^{-1}$ (winter).

Inputs to the river that may be contributing significant loads of uranium include: tributaries draining the foothills region to the North of the river, tributaries from the South of the river containing agricultural return flow, and shallow groundwater flows discharging to the river channel. Dry Creek and Willow Creek, two tributaries emanating from the foothills to the North, were found to have low uranium concentrations with max. values of 2.9 and 1.4 $\mu\text{g L}^{-1}$ respectively. Indian Creek and 10 Mile Creek, two southern tributaries which drain agricultural lands, were found to have uranium concentrations as high as 10.3 and 16.4 $\mu\text{g L}^{-1}$ respectively. In fact, sampling of Indian and 10 Mile Creeks revealed that they initially exhibit low uranium concentrations (similar to upstream Boise River water) in their upstream locations before undergoing a 10 to 20-fold increase at their downstream

locations. These trends are important because these waters are primarily affected by irrigation return waters, either via surface runoff or shallow groundwater discharge. In either case, these waters have only contacted surficial and near-surficial sediments. Additionally, surface waters consistently showed higher uranium concentrations during winter sampling, when shallow groundwater discharge to the river/stream channels would be expected to make up a larger proportion of the total channel flows. All surface water data is tabulated in **Appendix A**. These combined surface water results suggest that:

- 1) A surficial or near-surficial uranium source exists within the Treasure Valley.
- 2) Neither the sedimentary geology of the foothills to the North nor the granitic geology of the headwaters of the Boise River supply significant dissolved uranium.

Treasure Valley and Regional Surface Water Sampling Locations

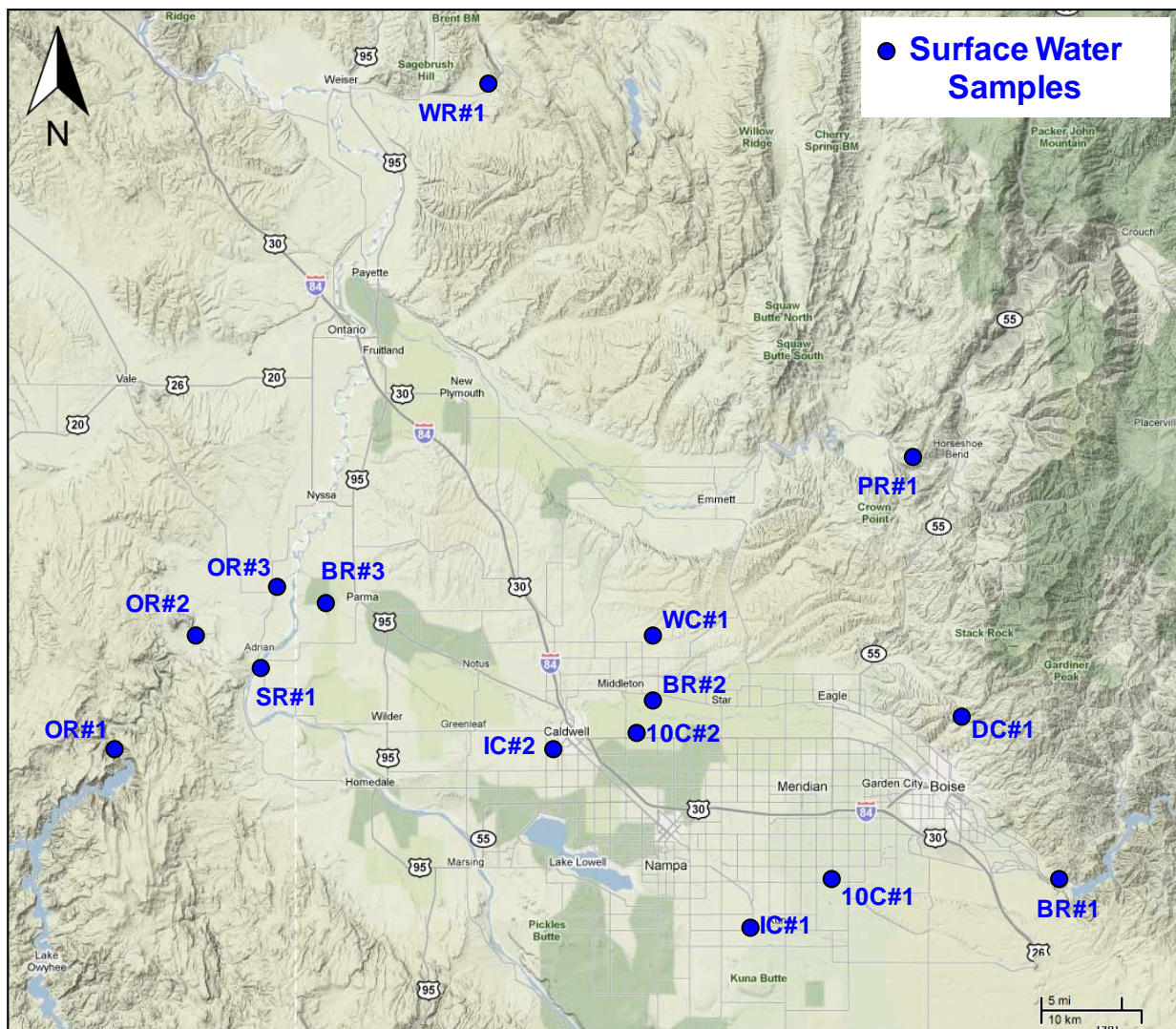


Figure 3: Map showing the locations of both Treasure Valley and regional surface waters included in the field sampling effort. More detailed descriptions of surface water samples are available in **Table 2**.

Table 2: Surface Water Sample Key

	Sample ID	Number of Samples	Data Available
Upstream Boise River	BR#1	2	Anion, Cation, Field, Isotope
Mid Boise River	BR#2	2	Anion, Cation, Isotope
Lower Boise River	BR#3	2	Anion, Cation, Field, Isotope
Dry Creek	DC#1	2	Anion, Cation, Isotope
Willow Creek	WC#1	2	Anion, Cation, Field, Isotope
Upstream 10 Mile Creek	10C#1	1	Cation, Field, Isotope
Downstream 10 Mile Creek	10C#2	3	Anion, Cation, Field, Isotope
Upstream Indian Creek	IC#1	1	Cation, Field, Isotope
Downstream Indian Creek	IC#2	3	Anion, Cation, Field, Isotope
Payette River	PR#1	2	Anion, Cation, Field, Isotope
Snake River	SR#1	2	Anion, Cation, Field, Isotope
Weiser River	WR#1	2	Anion, Cation, Field, Isotope
Upstream Owyhee River	OR#1	1	Cation, Field, Isotope
Mid Owyhee River	OR#2	1	Cation, Isotope
Downstream Owyhee River	OR#3	3	Anion, Cation, Field, Isotope

Letters following the sample ID are used to denote repeated samplings at the same location. Surface waters were sampled (a) Sept. 2009, (b) Feb. 2010, and (c) Aug. 2010.

Another key finding related to surface water sampling is the suggestion of a distinct isotopic signature of the uranium source. As previously mentioned, several regional rivers were sampled in addition to those within the Boise River Watershed. The isotopic compositions of all surface waters are presented in **Figure 4**. Notice that the isotopic compositions of the Boise River, Indian Creek, 10 Mile Creek, and the Owyhee River all begin at their upstream sampling location exhibiting very different isotopic compositions, but as uranium concentrations increase, those isotopic signatures evolve towards a central nexus of convergence. In other words, as concentrations increase downstream in each of these surface waters, the isotopic signature becomes more similar to each other. The fact that these different waters all exhibit increased downstream uranium and converging downstream isotopic compositions provides strong evidence that they are all likely influenced by a common uranium source. The isotopic signature of that source material is identified by the region in uranium-strontium isotopic space toward which the waters are evolving.

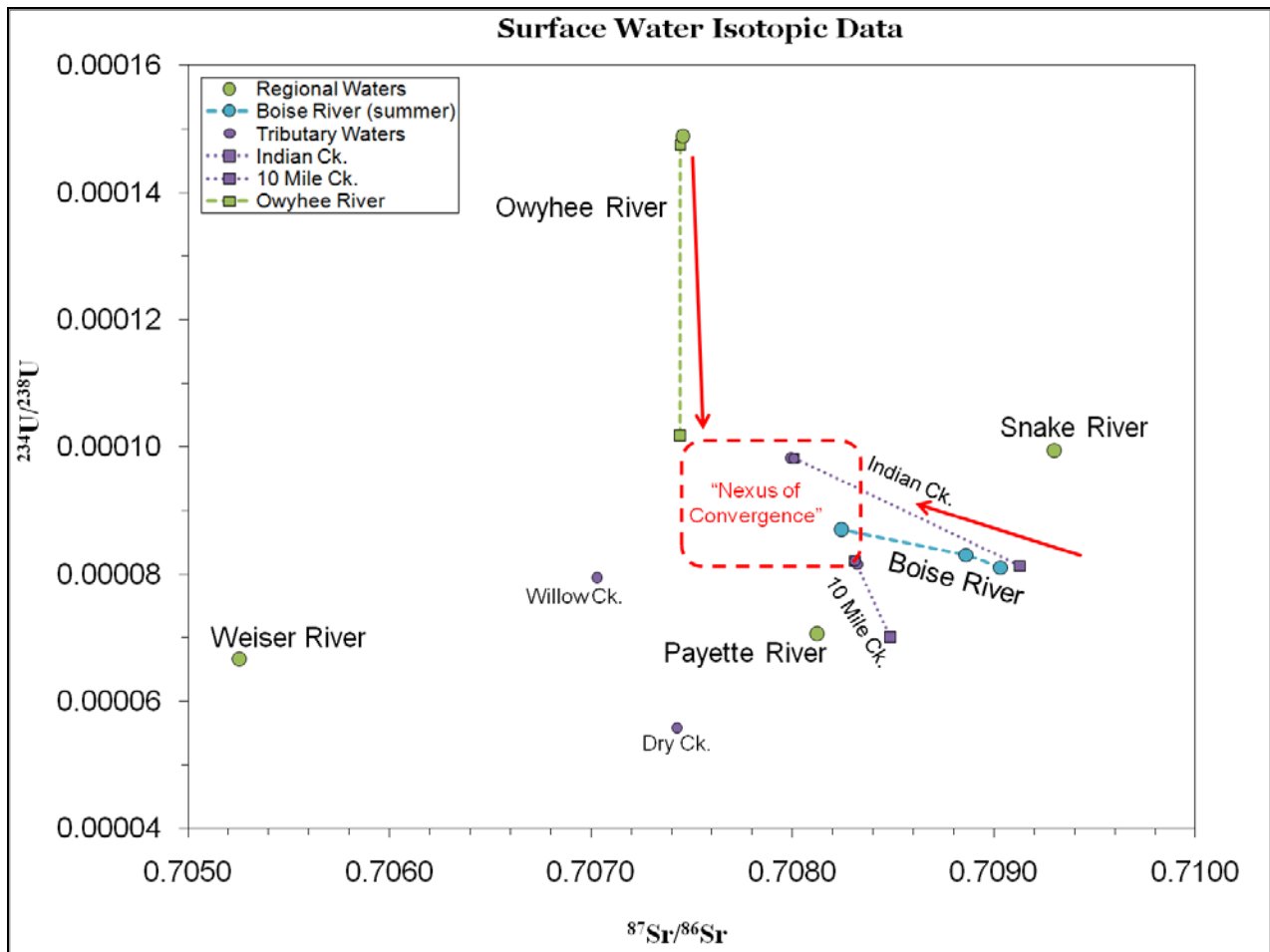


Figure 4: Boise River Watershed and regional river isotopic compositions. Arrows indicate the direction towards which the waters are evolving as sampling progresses downstream.

4.3 Groundwater

The isotopic compositions of the groundwater well samples collected for this study are added to the plot in **Figure 5**. While there is some scatter among the eight wells, they identify a diffuse, but distinct cluster when compared to the diverse isotopics present within the region. It can be seen that at least half of the well samples plot within, or at a close proximity to, the surface water uranium source nexus. Only one well sample clearly diverges from source nexus. The wells nearest to the nexus are the most clearly affected by the uranium source influencing the surface waters. Those wells that plot further from the nexus are likely affected by a separate (but similar) source, or a mixture of sources. Additionally, it should be noted that among the eight well samples, the three with the highest uranium concentrations all plot in the low $^{234}\text{U}/^{238}\text{U}$ and high $^{87}\text{Sr}/^{86}\text{Sr}$ corner of the cluster (circled in red). All groundwater sample descriptions, data, and mapped locations are available in **Appendix B**.

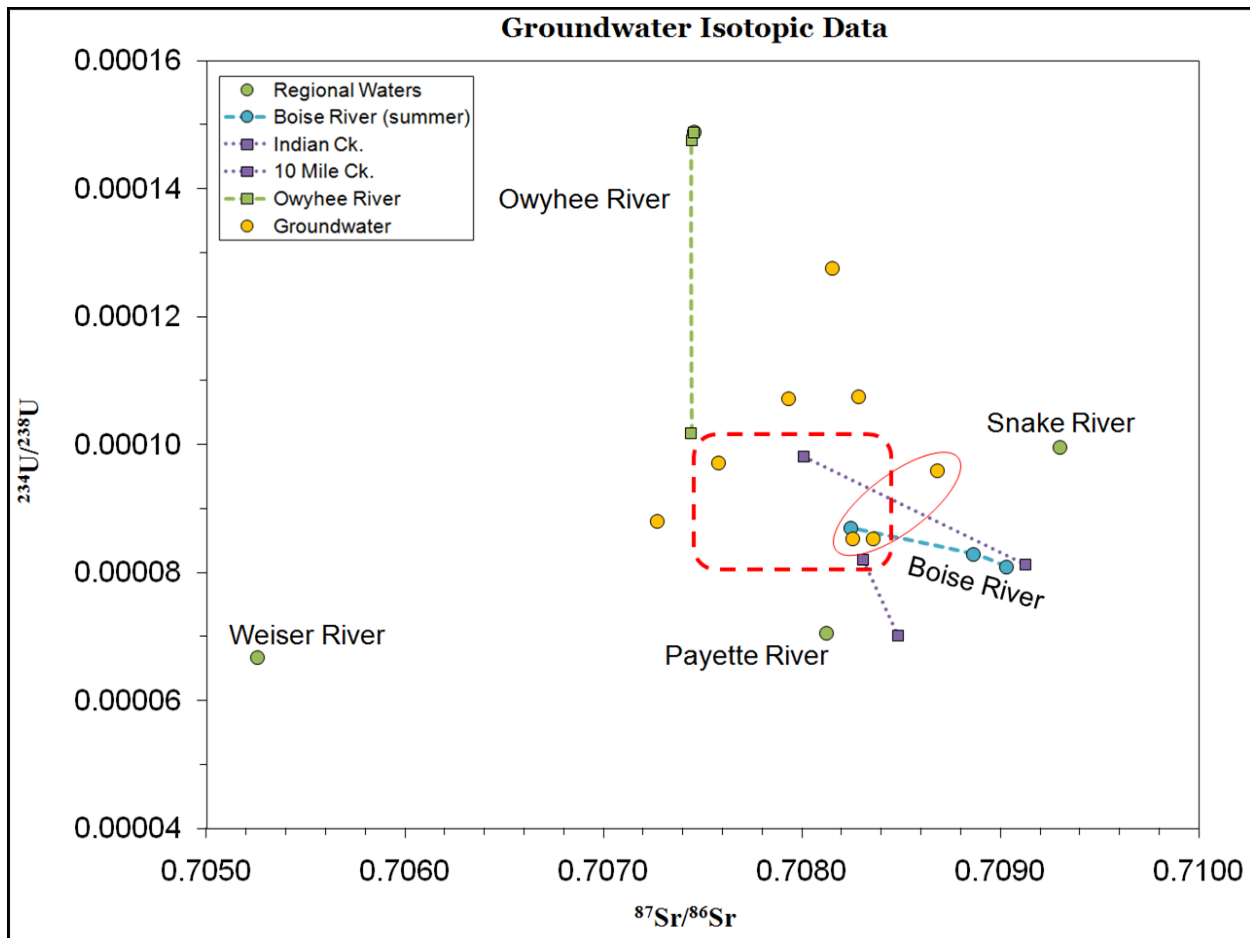


Figure 5: Isotopic composition of groundwater samples in relation to regional surface waters. The cluster of golden circles represents the eight wells sampled, with the highest uranium concentrations circled in a solid red line.

4.4 Solids Analysis

The solids analysis served to address several questions. Among them: Do Treasure Valley aquifer sediments contain unusually high uranium contents? Does the uranium in phosphate fertilizers match the isotopic signature of the elevated uranium source? Can any Treasure Valley geologic formations yield isotopic compositions matching the signature of the uranium source?

Among the wide variety of lithologies collected, none of the solids were remarkably uraniumiferous (**Table 3**). The average total uranium content of the solids was approximately 3.4 ppm, generally consistent with average uranium content of continental crustal materials of 2.7 ppm and global average granitic materials averaging 4.4 ppm (Wanty and Nordstrom, 1995). In contrast, phosphate fertilizer samples and the phosphate ore rock from which they are made yielded high uranium contents ranging from 38 to 319 ppm.

While overall uranium concentrations for the Treasure Valley sediments are low, the selective leaching experiments indicate that certain fractions of the solids hold more uranium than others. Carbonate rich solids and solids heavy in iron/manganese oxide coatings released the most water soluble uranium. On average, the extraction targeting carbonate materials released the highest uranium concentrations of the three leaching treatments.

Table 3: Total U Content of Solids and Phosphate Samples

	Formation	U Conc. (ppm)
Topsoil / loess	Gowen Terrace	4.0
Carbonate-rich horizon	Gowen Terrace	7.0
Coarse sand	Gowen Terrace	2.3
Fe Oxide stained silty clay	Gowen Terrace	3.7
Gray silty clay	Gowen Terrace	3.6
Silt	Calcareous Glens Ferry	4.4
Fe Oxide-rich sand	Chalk Hills	4.5
Ash	Chalk Hills	3.0
Silt / clay	Chalk Hills	3.3
Loess	Glens Ferry	3.0
Carbonate-rich horizon	Glens Ferry	2.9
Fe Oxide-rich sand	Glens Ferry	1.2
Silt	Glens Ferry	5.7
Ash	Glens Ferry	3.0
Coarse Sand	Pierce Gulch	0.9
Silt	Pierce Gulch	5.0
Loess	Kuna Butte	3.4
Phosphate Ore (weathered)	Phosphoria	76
Phosphate Ore (unaltered)	Phosphoria	225
Fertilizer S		38
Fertilizer L		271
Fertilizer H		319

Wanty and Nordstrom (1995) provide estimates of average uranium content in geologic solids: 2.7 ppm for all crustal materials and 4.4 ppm for granitic materials.

The isotopic contents resulting from the leaching experiments ultimately dictate which solids can be potentially implicated as the uranium source(s) in the Treasure Valley. Uranium in Treasure Valley Groundwater

Figure 6 displays the isotopic results from both the solids leaching and phosphate fertilizer experiments. Particularly noteworthy is that all phosphate fertilizer and ore samples consistently exhibit very low $^{234}\text{U}/^{238}\text{U}$ ratios and, therefore, cannot be the source of uranium found in the Treasure Valley. In fact the vast majority of geologic samples collected exhibit ratios that are incompatible with the elevated uranium source signature, primarily due to the fact that the solids exhibit significantly lower $^{234}\text{U}/^{238}\text{U}$ ratios. One sample seems to break the low $^{234}\text{U}/^{238}\text{U}$ ceiling and plots within the nexus representing the uranium source. This sample was a fine-grained layer found within the Gowen Terrace formation. Interestingly, other sediments from different units in the Gowen Terrace exhibit low uranium isotope ratios and cannot be the source of observed uranium. Solid sample descriptions, data, and mapped collection locations are available in **Appendix C**.

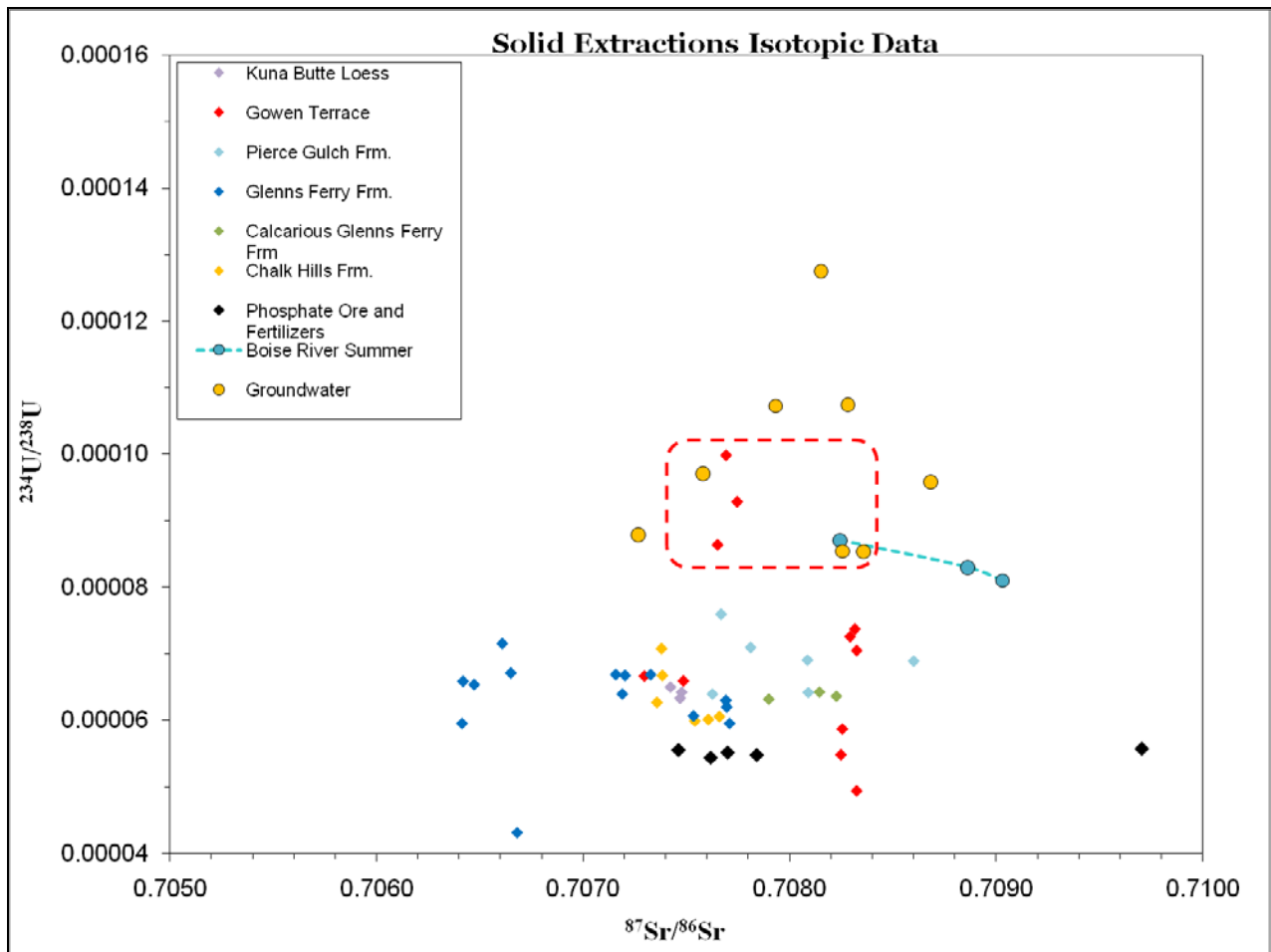


Figure 6: Isotopic compositions yielded by selective leaching of geologic solids and phosphate samples. Solids are grouped by their geologic formation. Formations are listed in order of increasing depth below the current ground surface.

4.5 Discussion

The spatially distributed, but sporadic, nature of elevated uranium in the groundwater of the Treasure Valley (**Figure 1**) suggest that either the source of (or the conditions for) uranium release may not exist ubiquitously, but rather in specific locations or stratigraphic depths. This theory is also supported somewhat by the results of the isotopic analysis of Gowen Terrace solids, in that a wide range of different isotopic compositions are represented by the different lithologies present within the terrace. If other terrace sediments comprising the shallow aquifer are similarly variable, then it would be easy to imagine how uranium levels could be contrasting in wells of close proximity.

It should be noted that the statistics presented in **Table 1** do not necessarily represent the absolute distribution of uranium concentrations in all Treasure Valley wells. For example, among public wells, locations which have previously demonstrated very low uranium concentrations may be granted the privilege of testing for uranium less frequently while high uranium wells may be tested more frequently. This administrative strategy could skew the public portion of the dataset toward including fewer wells with histories of low uranium. Conversely, because the public wells are regulated and required to rectify any contamination issues, the public portion of the dataset is likely skewed towards including mostly “cleaner” wells. The private well portion of the dataset is independent from the public data, and may represent a more random sampling of wells drawing from the shallow Treasure Valley aquifer.

The presence of a near surface uranium source, as evidenced by surface water concentration and isotopic data, stands in contrast to the lack of a relationship between uranium concentration and well depth shown in **Figure 2**. There are several data quality issues that may be limiting the ability of efforts to accurately depict the depth from which a large number of wells are drawing water. Close inspection of some well construction logs reveals that issues limiting the accuracy of well depth data include: incomplete information on well construction techniques, wells being screened at multiple depths, altogether missing well logs, and older well seals tending to poorly isolate the screened interval. Conducting a study with a clear focus on creating or finding “nests” of appropriately constructed wells in close proximity to each other would be useful in clarifying the potential relationship between uranium and well depth.

The strong association detected between uranium and carbonates/alkalinity both in groundwater chemistry and selective leaching experiments only provides further support for the trend identified in a previous Treasure Valley study (Cosgrove and Taylor, 2007). It is not yet clear whether this correlation is best explained as the dissolution of carbonate minerals as a uranium source, or the ability of alkaline water to efficiently mobilize uranium from non-carbonate sources. In either scenario, the trend between uranium and carbonate may be strong enough that conducting simple and inexpensive alkalinity testing could be promoted as a preliminary test of the potential for high uranium concentrations within groundwater wells.

Among the variety of solids analyzed for potential to be a uranium source material, only one fine-grained sample from Gowen Terrace matched to isotopic source signature. While the geologic material represented by this one sample likely cannot explain the extensive spatial distribution of high uranium waters, it helps to provide a framework to constrain future searches for more occurrences of potential sources. Being able to discount deeper aquifer sediments, coarse terrace sands, and loessial topsoil provides a much more focused set of remaining lithologies. The remaining list of suspected source materials most notably include young (Holocene epoch), fine grained terrace and floodplain sediments, as well as any sedimentary materials that can be traced back to relatively young igneous formations.

5 Conclusions and Recommendations

Existing data show that there are relatively few areas within the valley that appear to be immune to elevated uranium concentrations. However, as widespread in extent as the elevated uranium concentrations are, they are equally intermittent in their distribution. This speaks to the complexity of the behavior of uranium in the Treasure Valley. While the source and systematics of uranium have not yet been fully characterized, this study presents substantive findings to further constrain the understanding of this important issue.

The widespread increase in uranium concentrations in downstream surface waters is a strong indication of a near surface source. The isotopic evidence is also compelling. The fact that multiple Treasure Valley surface waters and a separate regional river all evolve towards a single isotopic nexus provides strong evidence that a common, but likely sporadically distributed, source material is releasing uranium to the system. At least half of the groundwater samples collected (including those with highest uranium concentrations) also have an isotopic character congruent with the source nexus. Isotopic results from solid leaching experiments do not support significant uranium release from deeper aquifer formations, loess samples, or fertilizer samples. Among limited samples from terrace materials, one sediment layer within the Gowen Terrace matched the isotopic signature of the source nexus. This near surface sample can focus further work to isolate uranium source solids in the Treasure Valley.

5.1 Groundwater Resource Management Implications

Based on these observations, several preliminary recommendations can be made. The isotopic data provides conclusive evidence eliminating the possibility that fertilizers are the source of uranium found in Treasure Valley groundwater; focus should remain on isolating the likely sedimentary source. Encouraging the extraction of groundwater from a

greater depth will reduce the possibility of encountering groundwater containing elevated uranium. Additionally, attention to properly isolating the screened interval from the overlying aquifer will limit contamination from overlying systems. The results of this study also suggest that groundwater alkalinity levels can be used as an inexpensive screening tool for uranium; elevated uranium is typically found in groundwater that is also high in alkalinity. Specifically, the available data indicate that an alkalinity value exceeding the 150-200 mg L⁻¹ range would be indicative of a need for further uranium testing.

5.2 Future Work

Recommendations for future work include:

- 1) More extensive sampling and analysis of additional “young” terrace and floodplain sediments.
- 2) Further investigation into the geologic characteristics of the Gowen Terrace sample that provides the best match to the elevated uranium source signature.
- 3) A more detailed investigation of the uranium concentration vs. aquifer depth relationship using nested monitoring wells.

6 References

- Blanco, P., F. Vera Tome, and J.C. Lozano (2005). Fractionation of Naturalized Radionuclides in Soils from a Uranium Mineralized Areas in the South-West of Spain. *Journal of Environmental Radioactivity* **79**: 315-330.
- Busbee, M.W., B.D. Kocar, S.G. Benner (2009). Irrigation Produces Elevated Arsenic in the Underlying Groundwater of a Semi-Arid Basin in Southwestern Idaho. *Applied Geochemistry* **24**: 843-859.
- Cosgrove, D.M., Taylor, J. (2007). Preliminary Assessment of Hydrogeology and Water Quality in Ground Water in Canyon County ID. *Idaho Water Resources Research Institute Technical Report 07-001*.
- Dhoum, R.T., and G.J. Evans (1998). Evaluation of Uranium and Arsenic Retention by Soil from a Low Level Radioactive Waste Management Site Using Sequential Extraction. *Applied Geochemistry* **13**(4): 415-420.
- 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.
- Johnson, T.M., R.C. Roback, T.L. McLing, T.D. Bullen, D.J. DePaolo, C. Doughty, R.J. Hunt, R.W. Smith, L.D. Cecil and M.T. Murrell (2000). Groundwater “Fast Paths” in the Snake River Plain Aquifer: Radiogenic Isotope Ratios as Natural Groundwater Tracers. *Geology* **28**(10): 871-874.
- La Force, M.J., and S. Fendorf (2000). Solid-Phase Iron Characterization During Common Selective Sequential Extractions. *Soil Science Society of America* **64**: 1608-1615.
- Langmuir, D. (1997). *Aqueous Environmental Geochemistry*. Upper Saddle River: Prentice-Hall, Inc. 1997.
- Martin, R., D.M. Sanchez, and A.M. Gutierrez (1998). Sequential Extraction of U, Th, Ce, La and Some Heavy Metals in Sediments from Ortigas River, Spain. *Talanta* **46**:1115-1121.
- Petrich, C. R., S.M. Urban (2004). *Characterization of ground water flow in the lower Boise River Basin*. Idaho Water Resources Research Institute.
- Roback, R. C., T. M. Johnson, T. L. McLing, M. T. Murrell, S. D. Luo and T. L. Ku (2001). Uranium Isotopic Evidence for Groundwater Chemical Evolution and Flow Patterns in the

Eastern Snake River Plain Aquifer, Idaho. *Geological Society of America Bulletin* **113**(9): 1133-1141.

Schmitz, M.D. and Bowring, S.A. (2001). U-Pb Zircon and Titanite Systematics of the Fish Canyon Tuff: An Assessment of High-Precision U-Pb Geochronology and Its Application to Young Volcanic Rocks: *Geochimica et Cosmochimica Acta* 65:2571-2587.

Schultz, M.K., W.C. Burnetta, and K.G. Inn (1998). Evaluation of a Sequential Extraction Method for Determining Actinide Fractionation in Soils and Sediments. *Journal of Environmental Radioactivity* **40**(2): 155-174.

Squires, E. & Wood, S. H. (2001). *Stratigraphic Studies of the Boise (Idaho) Aquifer System Using Borehole Geophysical Logs with Emphasis on Facies Identification of sand Aquifers*. Prepared for the Treasure Valley Hydrologic Study, Idaho Department of Water Resources.

Tessier, A., P.G.C. Campbell, and M. Bisson (1979). Sequential Extraction Procedure for the Speciation of Particulate Trace Metals. *Analytical Chemistry* **51**(7)844-851. Urban, S. M. (2004). *Water budget for the Treasure Valley aquifer system; Treasure Valley Hydrologic Project*. Idaho Department of Water Resources.

Thomas, R.P., A.M. Ure, C.M. Davidson, and D. Littlejohn (1994). Three-stage Sequential Extraction Procedure for Determination of Metals in River Sediments. *Analytica Chimica Acta* **286**: 423-429.

Wanty, R.B., D.K. Nordstrom (1995). Natural Radionuclides. In *Regional Ground-Water Quality*, ed. W.M. Alley. Van Nostrand Reinhold. 1995.

Zielinski, R. A., S. AsherBolinder, A. L. Meier, C. A. Johnson and B. J. Szabo (1997). Natural or Fertilizer-Derived Uranium in Irrigation Drainage: A Case Study in Southeastern Colorado, USA. *Applied Geochemistry* **12**(1): 9-21.

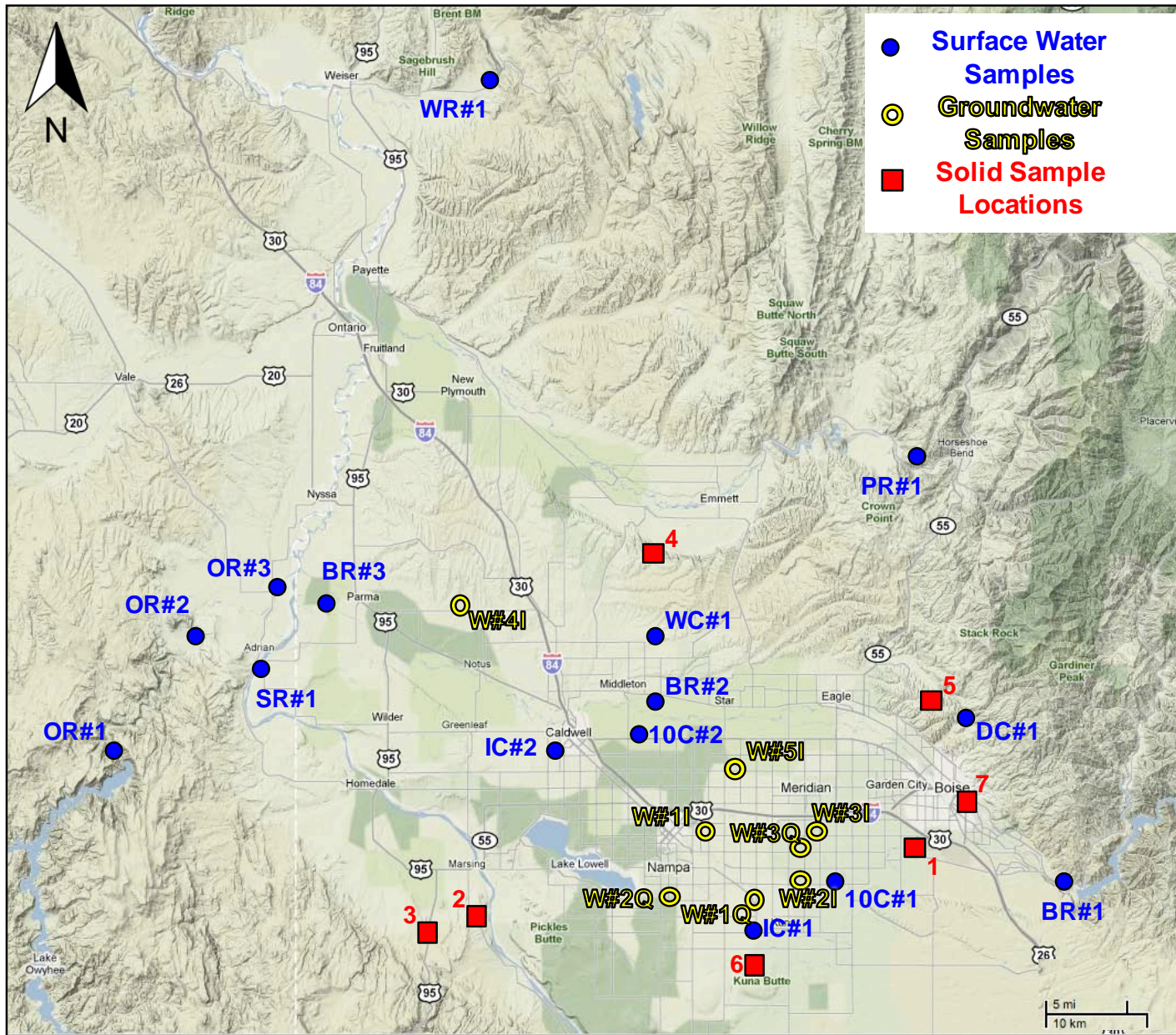
Zielinski, R. A., W. H. Orem, K. R. Simmons and P. J. Bohlen (2006). Fertilizer-Derived Uranium and Sulfur in Rangeland Soil and Runoff: A Case Study in Central Florida. *Water Air and Soil Pollution* **176**(1-4): 163-183.

Zielinski, R. A., K. R. Simmons and W. H. Orem (2000). Use of U-234 and U-238 Isotopes to Identify Fertilizer-Derived Uranium in the Florida Everglades. *Applied Geochemistry* **15**(3): 369-383.

7 Appendix A

7.1 Surface Water Data Summary

7.2 Map of Surface Water, Groundwater, and Solid Sample Collection Locations



Geochemical Data for Surface Water Samples

		analytical instrument	detection limit	instrument accuracy (+/-)	instrument precision (+/-)	blank	BR#1 a	BR#1 b	BR#2 a	BR#2 b	BR#3 a	BR#3 b	DC#1 a	DC#1 b	WC#1 a	WC#1 b
²³⁴ U/ ²³⁸ U		TI-MS					0.0000810	0.0000791	0.0000830	0.0000841	0.0000871	0.0000892	0.0000559	0.0000541	0.0000712	0.0000795
[²³⁴ U/ ²³⁸ U]		TI-MS					1.48	1.44	1.51	1.53	1.59	1.62	1.02	0.986	1.30	1.45
⁸⁷ Sr/ ⁸⁶ Sr		TI-MS					0.70903	0.70882	0.70886	0.70874	0.70824	0.70819	0.70743	0.70740	0.70797	0.70703
Na	(µg/L)	ICP-MS	5	7.4%	1.3%	0.104	3,159	4,048	11,480	18,110	31,120	44,270	8,028	7,547	4,461	14,440
Mg	(µg/L)	ICP-MS	1	6.5%	1.4%	0.479	906.8	1,133	2,243	3,209	8,489	11,420	2,353	1,993	1,099	5,553
Si	(µg/L)	ICP-MS	10	11.7%	1.4%	10.1	4,955	5,444	5,589	5,277	10,680	12,630	12,430	11,380	4,275	10,200
K	(µg/L)	ICP-MS	5	13.3%	1.3%	5.22	538.7	514.0	1,504	2,066	3,525	4,252	1,557	968.9	833.5	3,672
Ca	(µg/L)	ICP-MS	5	8.0%	1.2%	3.35	8,654	9,749	14,850	19,050	31,240	38,570	22,710	20,210	7,056	22,160
Sr	(µg/L)	ICP-MS	0.05	3.6%	1.0%	0.023	83.55	102.0	140.2	178.2	233.9	283.4	277.2	252.6	84.88	213.9
Ba	(µg/L)	ICP-MS	0.5	9.0%	1.0%	0.033	8.822	11.81	16.16	23.57	40.14	47.91	44.87	37.27	16.52	62.61
U	(µg/L)	ICP-MS	0.01	2.2%	1.6%	0.013	0.322	0.632	1.253	2.916	5.637	9.884	1.864	2.854	0.138	1.425
Cr	(µg/L)	ICP-MS	0.05	3.2%	5.3%	0.041	0.006	0.104	0.011	0.212	0.167	0.658	0.032	0.190	0.000	0.368
Mn	(µg/L)	ICP-MS	1	3.2%	2.3%	0.057	1.121	0.541	27.16	30.28	14.08	22.87	4.910	1.616	9.623	22.13
Fe	(µg/L)	ICP-MS	5	6.6%	10.3%	0.000	22.75	12.71	43.29	20.78	16.94	10.97	44.57	18.13	34.90	161.4
Ni	(µg/L)	ICP-MS	0.01	2.4%	7.2%	0.000	0.229	0.157	0.368	0.421	0.856	0.833	0.349	0.238	0.172	1.506
Cu	(µg/L)	ICP-MS	0.05	2.5%	12.1%	0.019	0.566	0.071	0.566	0.674	0.794	0.536	0.000	0.000	1.509	4.615
Zn	(µg/L)	ICP-MS	0.05	1.6%	5.4%	0.203	21.76	0.140	3.548	5.283	1.997	2.777	0.759	0.255	1.252	2.577
Cd	(µg/L)	ICP-MS	0.05	2.3%	25.8%	0.012	0.000	0.007	0.000	0.007	0.006	0.030	0.025	0.022	0.000	0.126
Pb	(µg/L)	ICP-MS	0.01	1.9%	12.6%	0.010	0.000	0.011	0.000	0.041	0.006	0.072	0.020	0.020	0.000	0.236
Al	(µg/L)	ICP-MS	1	11.5%	4.9%	0.336	17.66	13.09	1.863	1.350	3.321	1.590	3.197	20.78	7.485	180.3
P	(µg/L)	ICP-MS	10	11.8%	7.1%	2.83	16.75	0.000	241.1	397.5	252.5	358.1	52.66	21.54	22.72	90.75
As	(µg/L)	ICP-MS	0.05	2.4%	12.0%	0.144	2.201	2.202	3.094	2.292	6.480	6.901	3.947	1.627	4.112	48.78
Se	(µg/L)	ICP-MS	0.5	28.6%	32.0%	0.000	0.000	0.000	0.000	0.000	0.241	0.589	0.033	0.163	0.323	0.420
Br	(mg/L)	IC	0.025	12.0%	4.9%	0.003	0.000	0.007	0.011	0.035	0.042	0.074	0.000	0.007	0.005	0.015
Cl	(mg/L)	IC	0.25	7.3%	4.5%	0.125	0.554	0.600	5.73	12.2	11.9	21.8	0.935	2.06	0.692	4.42
F	(mg/L)	IC	0.025	4.0%	8.4%	0.022	0.237	0.316	0.314	0.426	0.386	0.471	0.109	0.109	0.347	0.290
NO₃	(mg/L)	IC	0.025	5.2%	1.1%	0.020	0.012	0.025	0.603	2.12	1.790	4.66	0.012	0.218	0.000	0.217
NO₂	(mg/L)	IC	0.05	12.8%	13.6%	0.011	0.000	0.015	0.000	0.000	0.000	0.007	0.000	0.004	0.000	0.002
PO₄	(mg/L)	IC	0.025	6.0%	5.8%	0.000	0.007	0.000	0.197	0.316	0.182	0.279	0.035	0.016	0.008	0.067
SO₄	(mg/L)	IC	0.5	12.0%	5.6%	0.167	1.74	2.20	6.88	11.1	27.3	41.7	1.59	2.43	1.30	30.7
Alkalinity	(mg/L CaCO ₃)	field kit		15%	15%		25	42			110	160			32	75
pH	std. unit	multi-meter		0.1 std. unit	0.05 std. unit		7.6	7.7			8.3	8.1			7.5	7.8
DO	(mg/L)	multi-meter		1.5 mg/L	1.0 mg/L		7.3	14			13	14			9.3	16
ORP	(mV)	multi-meter		25%	15%		19	-73			-12	-94			-1.5	-99
Spec. Cond	(µS/cm)	multi-meter		15%	5%		70	130			380	750			69	360

Uncertainty (+/- 1σ) associated with isotopic data generated by TI-MS analysis is less than 0.56% for all ²³⁴U/²³⁸U samples and less than 0.0008% for all ⁸⁷Sr/⁸⁶Sr samples.

Analytical instruments/methods used include: (TI-MS) multi-collector thermal ionization mass spectrometry, (ICP-MS) inductively coupled plasma mass spectrometry, (IC) ion chromatography, (multi-meter) handheld field water chemistry meter, and (field kit) colorimetric alkalinity kit.

Geochemical Data for Surface Water Samples

	10C#1 c	10C#2 c	10C#2 b	10C#2 a	IC#1 c	IC#2 c	IC#2 b	IC#2 a	PR#1 a	PR# 1 b	SR#1 a	SR#1 b	WR#1 a	WR#1 b	OR#1 c	OR#2 c	OR#3 c	OR#3 b	OR#3 a
$^{234}\text{U}/^{238}\text{U}$	0.0000701	0.0000821	0.0000843	0.0000816	0.0000813	0.0000982	0.000101	0.0000983	0.0000709	0.0000706	0.0000960	0.0000995	0.0000666		0.000149	0.000148	0.000102	0.0000939	0.000102
$^{234}\text{U}/^{238}\text{U}$	1.28	1.50	1.54	1.49	1.48	1.79	1.83	1.79	1.29	1.29	1.75	1.81	1.21		2.71	2.69	1.85	1.71	1.85
$^{87}\text{Sr}/^{86}\text{Sr}$	0.70849	0.70831	0.70815	0.70832	0.70913	0.70801	0.70785	0.70799	0.70820	0.70812	0.70906	0.70930	0.70525	0.70493	0.70746	0.70744	0.70744	0.70734	0.70739
Na	13,640	18,180	65,340	17,630	3,308	52,150	64,430	43,930	3,867	6,721	32,450	30,330	9,117	6,955	28,970	29,530	61,110	100,400	66,680
Mg	5,670	7,502	17,660	6,986	1,002	15,780	20,380	13,780	777.5	1,186	18,430	19,230	5,626	4,759	5,545	5,532	10,700	15,870	11,190
Si	12,670	11,200	15,530	10,560	5,411	20,330	20,460	17,760	4,764	6,646	9,216	13,600	15,840	11,640	6,705	5,672	15,250	15,060	13,420
K	4,185	2,638	6,429	2,364	509.8	8,987	8,150	6,043	666.5	778.3	4,755	4,680	3,290	1,881	3,468	3,437	6,675	8,259	6,209
Ca	25,160	27,800	56,000	25,610	9,509	50,170	62,740	46,350	6,158	10,500	44,640	48,090	13,150	11,370	20,940	20,750	42,110	57,540	41,150
Sr	198.3	228.4	430.9	213.6	85.71	287.9	331.8	265.3	78.95	132.1	266.1	274.5	74.87	56.42	99.84	98.23	178.0	227.2	178.5
Ba	52.89	44.65	69.88	39.40	8.895	61.85	67.12	55.68	10.87	14.57	42.11	42.16	49.01	10.76	16.21	15.57	32.92	28.04	28.25
U	0.479	5.176	16.35	4.612	0.439	8.059	10.32	6.626	0.286	0.901	3.838	3.495	0.133	0.123	1.653	1.652	4.720	7.905	5.193
Cr	0.912	0.887	0.555	0.091	0.238	2.255	1.256	0.495	0.000	0.193	0.589	1.389	0.544	0.208	0.890	0.773	1.611	1.035	0.259
Mn	26.23	6.580	23.63	6.813	3.339	7.507	17.69	9.439	8.286	11.993	8.615	5.707	12.31	21.38	0.951	3.874	55.76	52.40	38.75
Fe	38.34	6.935	6.978	30.08	2.112	1.301	4.194	29.39	23.17	38.22	10.88	1.078	1,117	59.14	18.04	14.82	264.4	78.34	31.40
Ni	1.138	0.794	1.088	0.607	0.200	1.152	0.793	0.969	0.069	0.102	0.849	0.642	1.403	0.505	0.825	0.829	1.770	1.504	1.550
Cu	0.914	1.380	1.544	2.415	0.547	1.247	0.388	0.798	0.000	0.000	0.339	0.333	2.698	0.758	0.852	0.742	1.349	0.743	0.587
Zn	2.658	1.696	12.86	2.798	1.649	4.530	2.202	2.470	0.928	0.327	1.626	0.184	8.283	0.007	1.751	0.730	1.777	0.516	1.610
Cd	0.000	0.001	0.019	0.000	0.000	0.000	0.007	0.000	0.000	0.028	0.025	0.022	0.021	0.029	0.000	0.000	0.016	0.079	0.000
Pb	0.008	0.016	0.076	0.006	0.004	0.032	0.018	0.040	0.000	0.018	0.036	0.049	0.186	0.042	0.020	0.019	0.272	0.131	0.000
Al	5.631	6.055	1.740	14.01	2.620	3.684	2.560	24.54	4.912	18.01	3.026	1.220	1,067	6.230	42.96	32.44	270.2	77.02	30.30
P	129.2	202.6	972.0	243.5	0.000	622.5	693.9	568.8	7.302	11.73	50.72	41.35	102.6	9.108	0.000	0.000	63.00	76.08	54.55
As	2.356	4.111	4.548	4.131	2.046	8.338	8.618	7.642	0.313	0.117	6.706	4.598	2.047	1.117	6.615	6.759	24.83	36.62	26.48
Se	0.000	0.000	1.746	0.201	0.000	0.168	2.940	0.753	0.000	2.314	1.319	1.179	0.092	0.001	0.000	0.000	1.411	5.470	2.063
Br			0.084	0.026			0.124	0.082	0.006	0.011	0.049	0.061	0.007	0.007				0.102	0.071
Cl			51.1	6.43			28.2	19.2	0.604	1.25	23.7	27.2	1.31	2.16				21.3	15.6
F			0.470	0.336			0.450	0.391	0.380	0.688	0.427	0.453	0.142	0.069				1.17	1.03
NO₃			6.60	1.770			9.71	4.540	0.000	0.023	1.12	1.70	0.002	0.004				3.04	1.96
NO₂			0.033	0.000			0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.012				0.000	0.000
PO₄			0.710	0.183			0.472	0.414	0.002	0.000	0.014	0.007	0.053	0.000				0.014	0.014
SO₄			51.6	15.1			69.0	44.2	1.15	2.07	56.0	51.1	4.23	3.77				141	88.7
Alkalinity	110	92	210	98	32	130			27	34	170	170	75	59	98		170	200	190
pH	7.4	8.1	8.5	8.1	8.1	8.1			8.1	8.0	7.9	8.4	8.4	8.2	8.6		7.9	8.2	8.0
DO	7.5	11	15	11	10	10			11	14	9.3	14	11	16	12		9	13	11
ORP	-12	-16	-110	-14	-10	-14			-29	-27	-34	-89	-32	-85	-8.4		-12	-84	-37
Spec. Cond	210	260	1000	270	70	550			60	110	520	660	150	170	370		730	980	590

8 Appendix B

8.1 Groundwater Sample Key

8.2 Groundwater Data Summary

8.3 Groundwater Sample Map

Groundwater Sample Key

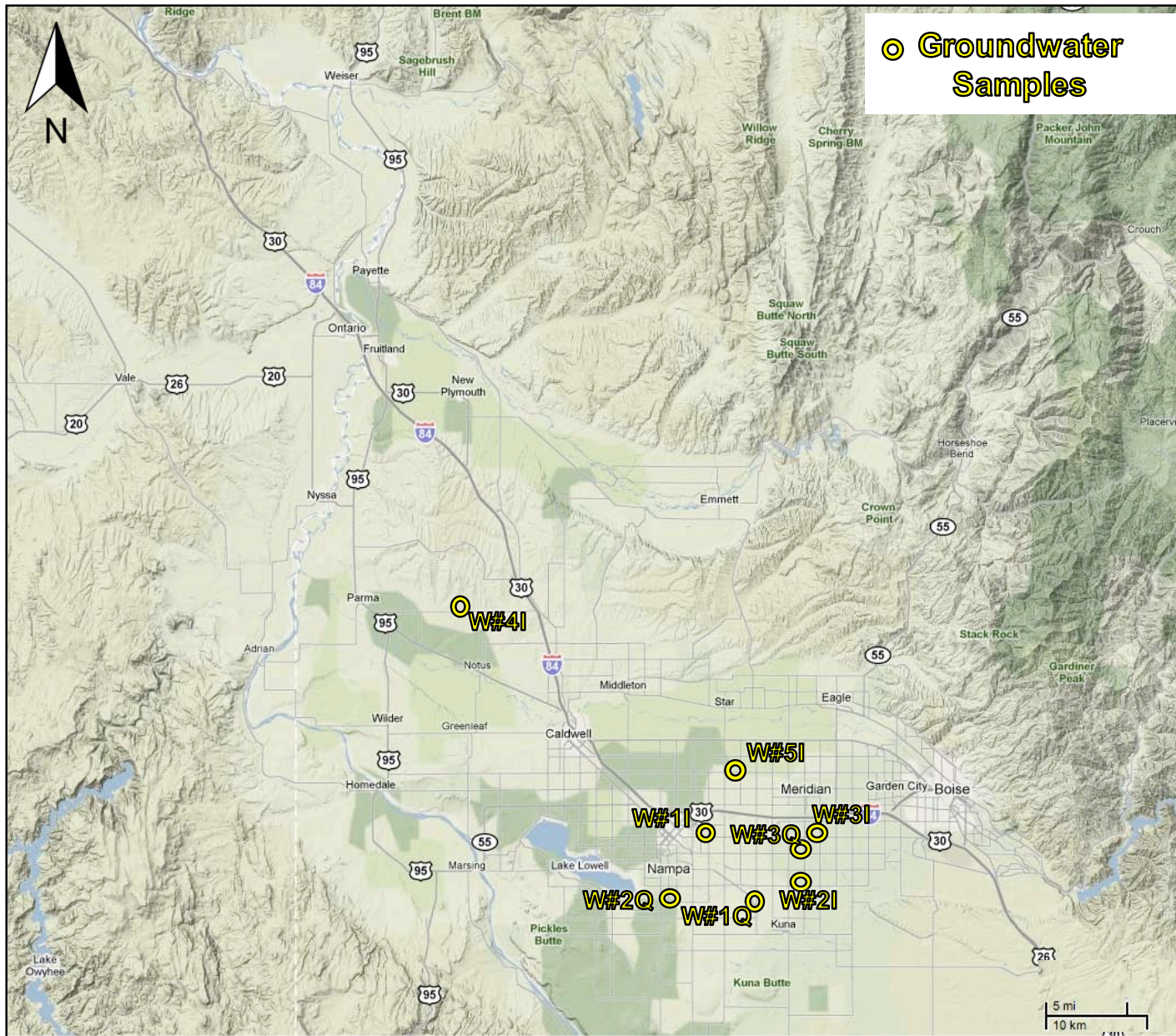
	Sample ID	Well Type	Data Available
Northern Nampa	W#1I	Private	Cation, Field, Isotope
South of Meridian	W#2I	Private	Anion, Cation, Field, Isotope
Southern Meridian	W#3I	Private	Anion, Cation, Field, Isotope
North of Notus	W#4I	Private	Anion, Cation, Field, Isotope
North of Nampa	W#5I	Private	Anion, Cation, Field, Isotope
Kuna	W#1Q	Public	Anion, Cation, Field, Isotope
Southern Nampa	W#2Q	Public	Anion, Cation, Field, Isotope
South of Meridian	W#3Q	Public	Anion, Cation, Field, Isotope

Geochemical and Field Data for Groundwater Samples

		analytical instrument	detection limit	instrument accuracy (+/-)	instrument precision (+/-)	blank	W#11	W#21	W#31	W#41	W#51	W#1Q	W#2Q	W#3Q
²³⁴ U/ ²³⁸ U [²³⁴ U/ ²³⁸ U] ⁸⁷ Sr/ ⁸⁶ Sr		TI-MS					0.000107	0.0000971	0.0000854	0.0000879	0.0000959	0.000128	0.000107	0.0000854
		TI-MS					1.96	1.77	1.56	1.60	1.75	2.32	1.95	1.56
		TI-MS					0.70828	0.70758	0.70826	0.70727	0.70868	0.70815	0.70793	0.70836
Na	(µg/L)	ICP-MS	5	4.6%	0.7%	0.776	47,620	87,450	108,300	62,740	89,030	60,380	68,310	65,710
Mg	(µg/L)	ICP-MS	1	7.4%	0.8%	0.713	8,836	12,000	10,870	7,114	20,230	16,130	12,620	16,830
Si	(µg/L)	ICP-MS	10	17.6%	0.9%	13.5	17,330	17,550	12,600	17,200	16,640	18,210	18,600	17,310
K	(µg/L)	ICP-MS	5	7.6%	0.7%	7.71	1,290	1,528	1,805	2,897	3,144	5,457	4,759	2,853
Ca	(µg/L)	ICP-MS	5	7.6%	0.7%	3.35	43,710	34,690	50,030	32,060	97,860	82,400	60,390	79,680
Sr	(µg/L)	ICP-MS	0.05	3.9%	0.6%	0.156	350.5	250.4	372.7	175.8	811.4	523.2	331.5	538.0
Ba	(µg/L)	ICP-MS	0.5	1.9%	0.6%	0.068	73.35	64.87	58.22	32.71	49.35	80.86	45.27	69.11
U	(µg/L)	ICP-MS	0.01	3.5%	0.7%	0.108	9.524	22.15	58.47	7.721	73.75	20.10	14.38	52.70
Cr	(µg/L)	ICP-MS	0.05	2.2%	4.2%	0.085	0.222	0.331	0.867	0.992	0.532	1.622	1.233	0.589
Mn	(µg/L)	ICP-MS	1	4.2%	8.9%	0.376	0.000	0.000	1.033	0.187	0.422	0.000	0.000	1.049
Fe	(µg/L)	ICP-MS	5	4.5%	4.6%	0.000	7.039	7.544	12.19	17.45	14.33	11.39	8.717	13.54
Ni	(µg/L)	ICP-MS	0.01	1.1%	4.4%	0.031	0.468	0.468	0.468	0.468	0.468	0.468	0.468	0.468
Cu	(µg/L)	ICP-MS	0.05	4.8%	2.1%	0.522	3.916	1.025	2.478	0.000	7.395	0.609	1.578	30.77
Zn	(µg/L)	ICP-MS	0.05	11.1%	1.1%	0.203	4.302	54.61	43.67	15.23	5.014	4.654	3.248	12.82
Cd	(µg/L)	ICP-MS	0.05	0.9%	25.8%	0.061	0.000	0.036	0.376	0.000	0.000	0.015	0.000	0.000
Pb	(µg/L)	ICP-MS	0.01	1.7%	5.7%	0.083	0.112	0.490	0.546	0.001	0.064	0.168	0.051	0.125
Al	(µg/L)	ICP-MS	1	2.9%	8.2%	0.336	0.351	0.372	1.148	0.502	0.390	0.495	0.062	0.083
P	(µg/L)	ICP-MS	10	6.7%	3.4%	2.83	40.37	35.71	34.74	79.63	121.6	23.48	19.18	43.41
As	(µg/L)	ICP-MS	0.05	2.5%	3.5%	0.144	1.471	3.969	1.124	9.134	2.066	3.384	3.419	1.240
Se	(µg/L)	ICP-MS	0.5	6.6%	14.7%	0.000	0.456	0.870	1.016	1.188	1.916	2.263	1.854	1.638
Br	(mg/L)	IC	0.025	12.0%	4.9%	0.011		0.057	0.044	0.110	0.114	0.251	0.110	0.096
Cl	(mg/L)	IC	0.25	9.9%	4.5%	0.549		15.6	15.4	18.8	21.6	30.1	15.1	9.3
F	(mg/L)	IC	0.025	12.4%	8.4%	0.014		0.510	0.666	0.551	0.271	0.085	0.436	0.198
NO₃	(mg/L)	IC	0.025	10.0%	1.1%	0.020		10.4	5.27	1.39	17.5	2.67	5.54	3.74
NO₂	(mg/L)	IC	0.05	12.8%	13.6%	0.018		0.000	0.000	0.000	0.000	0.000	0.000	0.000
PO₄	(mg/L)	IC	0.025	7.2%	5.8%	0.010		0.000	0.000	0.032	0.033	0.000	0.000	0.000
SO₄	(mg/L)	IC	0.5	12.0%	5.6%	0.516		37.3	47.6	57.4	116	150	88.4	86.8
Alkalinity	(mg/L CaCO ₃)	field kit		15%	15%		180	210	300	140	290	180	200	250
pH	std. unit	multi-meter		0.1 std. unit	0.05 std. unit		7.5	7.8	7.5	7.6	7.3	7.7	7.5	7.1
DO	(mg/L)	multi-meter		1.5 mg/L	1.0 mg/L		8.6	10	7.9	9.1	4.6	7.4	6.6	9.7
ORP	(mV)	multi-meter		25%	15%		36	10	94	-4.7	-13	25	-4	96
Spec. Cond	(µS/cm)	multi-meter		15%	5%		910	1200	760	480	930	740	660	730

Uncertainty (+/- 1σ) associated with isotopic data generated by TI-MS analysis is less than 0.18% for all ²³⁴U/²³⁸U samples and less than 0.0007% for all ⁸⁷Sr/⁸⁶Sr samples.

Analytical instruments/methods used include: (TI-MS) multi-collector thermal ionization mass spectrometry, (ICP-MS) inductively coupled plasma mass spectrometry, (IC) ion chromatography, (multi-meter) handheld field water chemistry meter, and (field kit) colorimetric alkalinity kit.



9 Appendix C

9.1 Solids Leach Sample Key

9.2 Solids Leach Data Summary

9.3 Solids Map

Solids Sample Key

	Sample ID	Approx. Depth (m)	Formation
Topsoil / loess	1#1	0.5	Gowen Terrace
Carbonate-rich horizon	1#2	2	Gowen Terrace
Coarse sand	1#3	8	Gowen Terrace
Fe Oxide stained silty clay	1#4	11	Gowen Terrace
Gray silty clay	1#5	12	Gowen Terrace
Silt	2#1	3	Calcareous Glenss Ferry
Fe Oxide-rich sand	3#1	2	Chalk Hills
Ash	3#2	5	Chalk Hills
Silt / clay	3#3	10	Chalk Hills
Loess	4#1	0.5	Glenss Ferry
Carbonate-rich horizon	4#2	3	Glenss Ferry
Fe Oxide-rich sand	4#3	8	Glenss Ferry
Silt	4#6	45	Glenss Ferry
Ash	4#7	55	Glenss Ferry
Coarse Sand	5#1	20	Pierce Gulch
Silt	5#2	35	Pierce Gulch
Loess	6#1	0.5	Kuna Butte

For each sample ID, the first number refers to the collection location (formation), and the second number portrays the depth within the stratigraphy from which the sample was collected.

Geochemical Data for Solid Leaching Experiments

Table with 13 columns for different sample IDs (183, 182, 183, 184, 185, 281) and rows for various elements (Na, Mg, Si, K, Ca, Sr, Cr, Mn, Fe, Ni, Cu, Zn, Cd, Pb, Al, P, As) measured in ppm. Each cell contains multiple values representing different measurements for that element.

Uncertainty (v/-) associated with isotopic data generated by Ti-MS analysis is less than 0.72% for all 234U/238U samples and less than 0.0088% for all 87Sr/86Sr samples.

Analytical instruments/methods used include: (Ti-MS) multi-collector thermal ionization mass spectrometry, (ICP-MS) inductively coupled plasma mass spectrometry.

Table with 13 columns for sample IDs (381, 382, 383, 481, 482, 483) and rows for various elements (Na, Mg, Si, K, Ca, Sr, Br, B, Cr, Fe, Ni, Cu, Zn, Cd, Pb, Al, P, As) measured in ppm. Each cell contains multiple values representing different measurements for that element.

Table with 13 columns for sample IDs (486, 487, 581, 582, 681) and rows for various elements (Na, Mg, Si, K, Ca, Sr, Br, B, Cr, Mn, Ni, Cu, Zn, Pb, Al, P, As) measured in ppm. Each cell contains multiple values representing different measurements for that element.

