URANIUM MOBILITY IN VEGETATION, SOILS AND WATER BELOW THE JACKPILE URANIUM MINE, NEW MEXICO

by
Michaella J. Gorospe

Master of Science in Geochemistry
New Mexico Institute of Mining and Technology
Earth and Environmental Science Department

Socorro, New Mexico
May 2013

ABSTRACT

The Jackpile uranium mine in north-west New Mexico, was one of the largest surface uranium mines in the world. Operations commenced in 1952 until a drop in uranium prices forced it to close in 1983. Some remediation of the mine site has been completed, and the mine continues to be a source of uranium contamination in nearby streams. Environmental sampling of the Rio San Jose and the Rio Paguate, on the Laguna Reservation, New Mexico, was conducted from 2009 to 2011. The purpose was to investigate uranium mobility from the closed Jackpile uranium mine in soils and vegetation. Plants totaling 96 of a variety of plant species, 46 soil samples and 6 water samples were collected from five sites on the Rio San Jose and Rio Paguate to determine which plants and locations were taking up and storing uranium and which locations were contaminated. Uranium concentrations in acid-digested plant tissue and soils was measured using an inductively-coupled plasma mass spectrometer (ICP-MS). Plant uranium content ranged from 23.62 ppm from an unidentified grass growing in water at the Paguate Reservoir, to below detection limits in plants from the Rio Paguate Reservoir and the Mesita diversion which was the sampling site farthest downstream of the Jackpile Mine. Plants including salt cedar and cattails growing near or in water had the highest uranium content. Soil

concentrations varied from a high of 31.44 ppm at the Paguate Reservoir to 0.32 ppm at the background site on the Rio San Jose. As expected, the background sites on the Rio Paguate and Rio San Jose comprised the lower ranges of uranium concentration in plants and soils. Water analysis ranged from a high of 0.46 ppm to a low of less than 0.05 ppm. Uranium in water did not correlate to the uranium content in the plants and soils.

The results of this study show that without the use of soil amendments or chelating agents, uranium is mainly being held in the soils and vegetation in the proximity of the mine in the Rio Paguate at the Paguate Reservoir and the exit of the mine. Concentrations of uranium farther downstream were much lower.

While the economic geology of the Laguna District has been extensively written about, relatively little attention has been paid to the environmental impact mining and milling has had on the stream systems and natural resources of the tribe. Jackpile Mine represents mining in an era before the enactment of surface mining reclamation law or state oversight. Currently, Laguna Pueblo conducts its own monitoring activities under the Clean Water Act with help from the U.S. EPA. In 2012 the Jackpile Mine site was added to the National Priority Listing where it becomes eligible for clean-up funds. This study compliments the data already gathered by the tribe for surface water to give a better understanding of the transport and storage of uranium from disturbed areas on the minesite.

Keywords: Jackpile Mine; uranium; Laguna Pueblo.

ACKNOWLEDGMENTS

I would like to thank my committee members: Dana Ulmer-Scholle, Bruce Harrison and Andy Campbell.

This work was completed with support from the Kottlowski Fellowship through the New Mexico Bureau of Geology and Mineral Resources, and the Minority Scholarship through the NMT Graduate Studies Office. A special thank you to Peter Scholle for his assistance in providing my funding. I also would like to thank Bonne Frey for instruction and use of the lab facilities, equipment and materials. Thank you to the Pueblo of Laguna Environmental Department, especially Curtis Francisco and Dorothy Beecher who provided me with transportation, history and access to my sample sites and shared data with me.

I would also like to extend my appreciation to the Rachael Dryer of the University of Wyoming American Heritage Collections Anaconda Collection, Eileen Vigil of the Bureau of Land Management and Iris of the Bureau of Indian Affairs for the insight they provided into the history of the Jackpile Mine and the use of that information today. Thank you to Ginger McLemore for allowing me access to her files on Jackpile.

For help in identifying the plants I gathered I would like to thank David Clark, Patrick Alexander, Bill McIntosh and Tom Dean.

Thanks to Mom & Dad, Ashley Arrossa, Dustin Baca, Vyoma Nenuji, Connie Apache and Alex Rinehart for their help and support in my research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

URANIUM MOBILITY IN VEGETATION, SOILS AND WATER DOWNSTREAM OF THE JACKPILE MINE, NEW MEXICO

CHAPTER 1

INTRODUCTION

1.1 Statement and Significance of the Problem

As many Western states are addressing legacy issues concerning uranium mining and milling, the Laguna Pueblo has similarly been grappling with the impact of the closure in 1982 of what was once the largest surface uranium mine, the Jackpile-Paguate Mine (Jackpile Mine). The Laguna Pueblo is comprised of six separate small villages situated along the Rio San Jose and Rio Paguate near Mount Taylor in northwest New Mexico. The village of Paguate is closest to the mine with the North Paguate pit highwall ending some 50 yards from Paguate homes (Figure 1). Uranium is of concern due to its toxicity as a heavy metal and its radioactivity especially when particles are ingested or inhaled as radon gas (Miera, 1980). Previous studies conducted by Popp et al. (1981), Novo-Gradac (1982) and Brandvold et al. (1981) show higher than background concentrations of uranium (U) in Rio San Jose sediments and water. In addition, tribal monitoring efforts show elevated levels of U in surface waters. This study is an attempt

to determine the concentration of uranium in native plant species and channel sediments in order to find possible storage sites on the Rio San Jose and Rio Paguate.

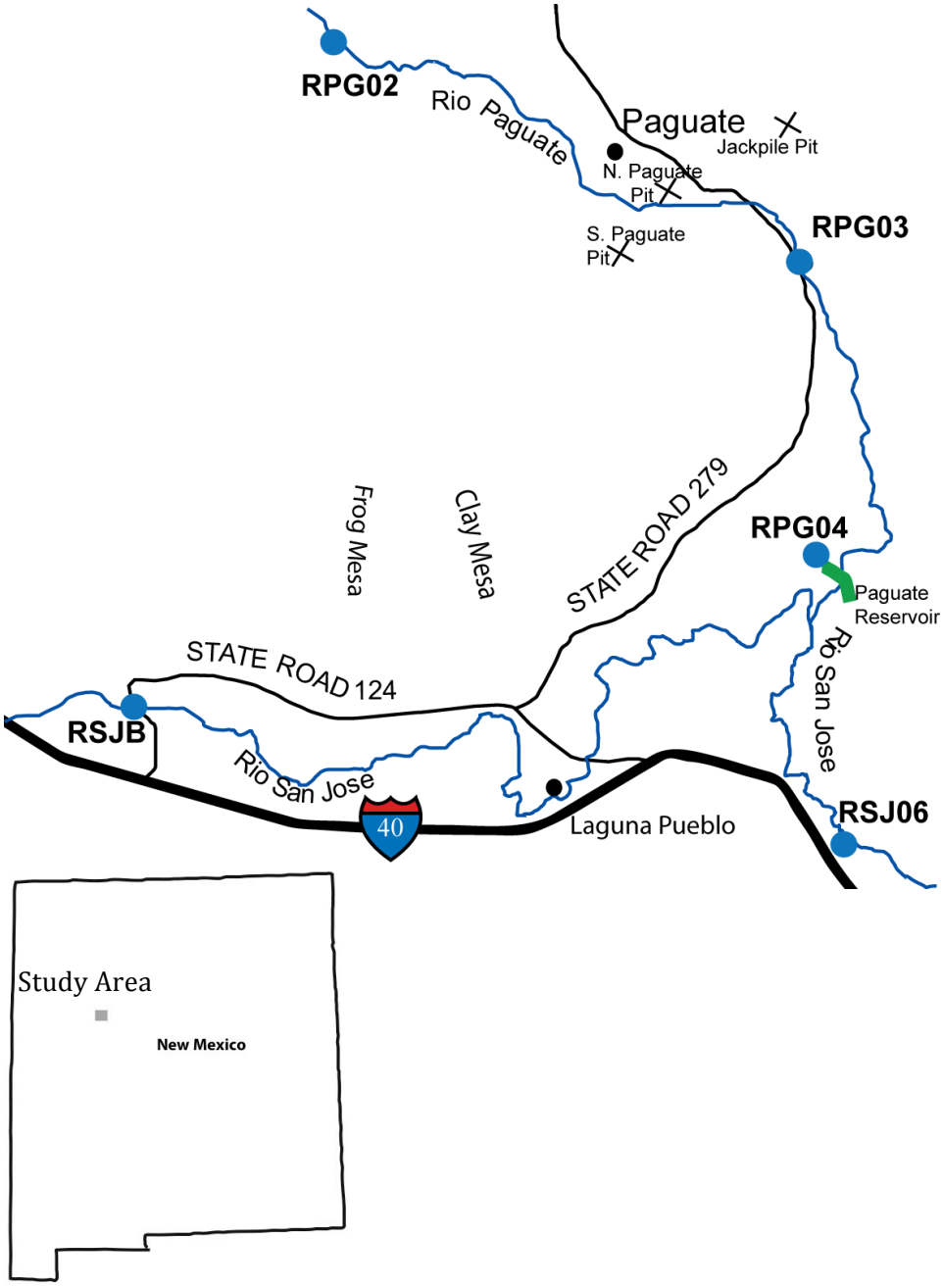


Figure 1. Map of study area and sampling locations.

The Jackpile Mine was part of the Laguna mining district and saw its peak in the 1960's and 70's (Figure 2). Originally, the mine was operated by Anaconda Company. For mining purposes, this area was called the Laguna district, and included uranium mines near the communities of Bibo and Marquez. The district was the easternmost portion of the Grants Uranium Belt, or Grants Mineral Belt that supplied a large amount of the nation's domestic uranium supply in the 1970's. The Laguna district covers approximately 535 square miles of the southeastern Colorado Plateau (Figure 2) (Moench and Schlee, 1967).

This mining district is located on the Laguna Indian Reservation and features several other abandoned and closed uranium mines. Jackpile Mine employed thousands of tribal members for work in the surface and underground operations. By 1970, 2.2 millon tons of ore had been mined between the Jackpile and Paguate pits that comprised the mine. Ore grade averaged between 0.22 and 0.32 U_3O_8 % (Holmquist, 1970).

After the mine ceased operation in 1982, reclamation commenced in 1992 with partial filling of the pits, and relocating of ore piles to at least 50 feet away from the Rio Moquino (Reith et al., 1993). This was meant to prevent further contamination of the stream by the exposed ore. The pueblo oversaw and carried out the majority reclamation. The pueblo continues to monitor both the mine site as well as the affected streams under the Clean Water Act, Section 106 (Pers. Comm., C. Francisco). Uranium concentrations above background concentrations in aqueous solution have been detected in waters from the Rio San Jose and Rio Paguate. Soil contamination and vegetation uptake of uranium have not been assessed by the Pueblo's Environmental Department.

The study area is naturally high in uranium. Soils are derived from the erosion of sandstone and shale bluffs, including the uranium bearing Jackpile Sandstone, and are deposited by eolian and fluvial processes. Vegetation along the streams is an important resource to the community; therefore, it is important to identify any uranium uptake by plants in the study area. Vegetation in this area is sometimes used as a fuel source in homes, and livestock graze around pools that collect shallow groundwater, or springs. In addition, preservation of traditional and cultural value of the water in these streams is of utmost importance to the Pueblo.

With the rising interest in resuming uranium mining in New Mexico, environmental impacts from these activities are coming under more scrutiny, including calls to clean up legacy issues prior to resumption of mining. Gathering information on the transport and retention of natural and anthropogenic uranium and other heavy metals will be critical. The Laguna Pueblo is assessing the environmental impact the Jackpile has on the reservation's land and water, this thesis can provide information the tribe can use in future remediation and reclamation efforts.

This study was performed in hopes of finding a sink for uranium along the Rio San Jose or Rio Paguate. This sink could be an area of the streams where sediments settle out. It was because of this that the two dams in the area were sampled. Vegetation was also investigated because some plants are known for the ability to take up uranium (Kuykendall, 2007; Neves, 2012). This study served to determine which plants in the study area may have phytoremediation potential.

This thesis will cover the important aspects of this research project in the Objective section. The Background will cover the regional geology, the geology of the

streams and the geology of the Jackpile Mine itself. A brief history of the Laguna Mining District including the Jackpile Mine is given. Uranium geochemistry is also discussed in this chapter. The Methods chapter goes over the field and laboratory procedures that were used in this study. The Results chapter presents the findings for all water, soil and vegetation analysis. These results are interpreted in the Discussion chapter. The Conclusion chapter will summarize the results and discussion as well as give some ideas for future work.

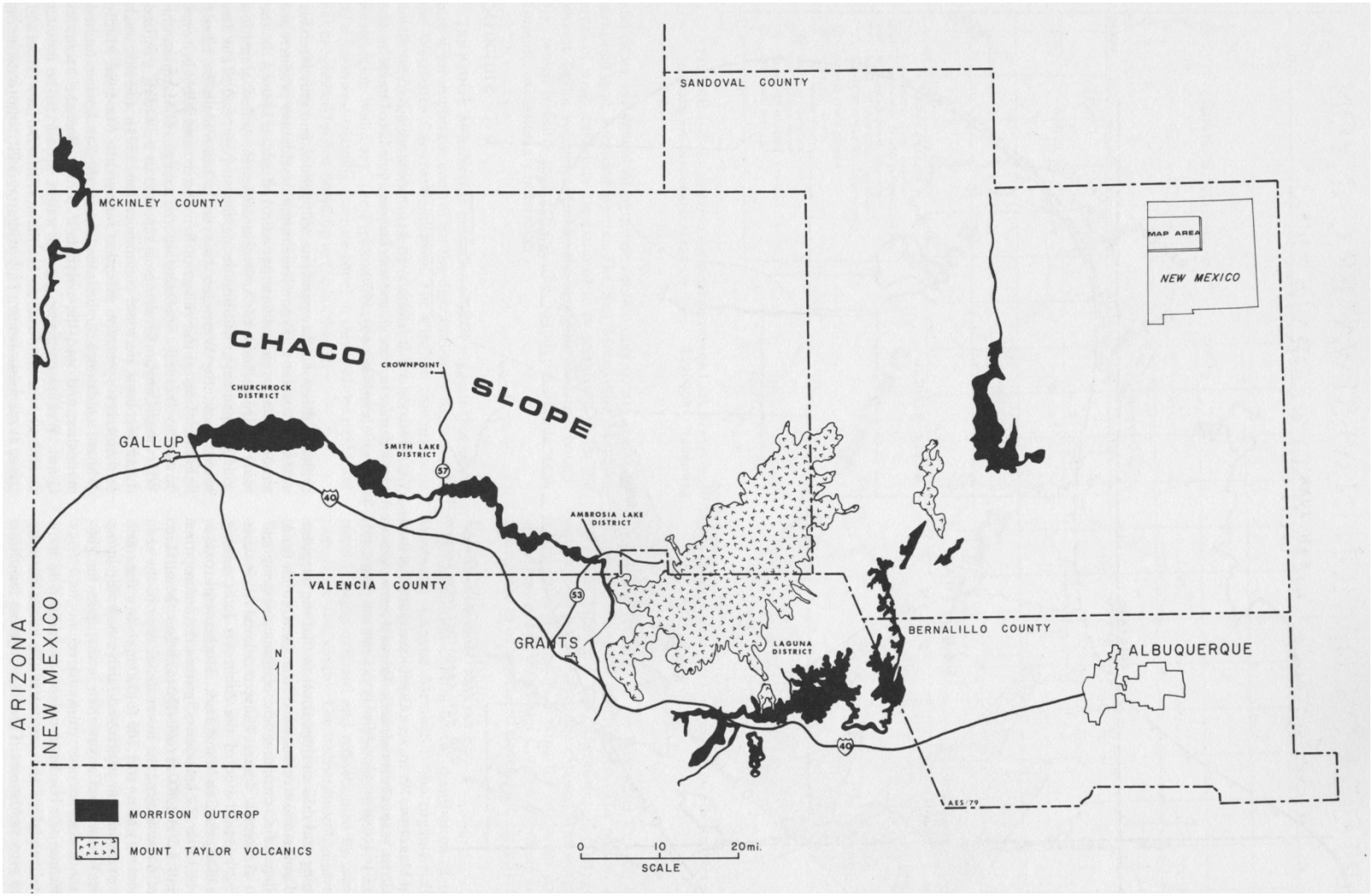


Figure 2. Historical map showing the Grants Mineral Belt (Saucier, 1979).

1.2 Objectives

The objective of this study is determine the concentration of uranium in vegetation and correlate that with the concentration of uranium in soils and surface waters at sampling locations along the Rio San Jose and the Rio Paguate drainages, downstream of the Jackpile Mine. Five sampling locations were chosen: two background sites and three sites of various distances downstream from mining activity (Figure 1). Locations of interest included the dams of Paguate Reservoir (RPG04) and the Mesita irrigation diversion (RSJ06); and the point on the Rio Paguate where the stream leaves the mine premises (RPG03). One background site was on the Rio San Jose near Casa Blanca, New Mexico (RSJB) and the other was on the Rio Paguate upstream of Paguate (RPG02).

This study attempts to find a correlation between uranium concentration in forbs, shrubs and grasses and the uranium content of sediments to assess uranium uptake by *in situ* vegetation. This information will provide data on the location and extent of uranium deposition downstream from the mine site. Knowing what plant species takes up the most uranium can be used in future remediation projects. The Jackpile Mine site is in the final stages of being added to the Superfund List that will address clean-up and reclamation of the area. In the future, phytoremediation could be a viable option for disturbed areas and areas with elevated uranium content along the Rio Paguate.

CHAPTER 2

BACKGROUND

2.1 Health Concerns Related to Uranium

Health problems can arise from ingestion and inhalation of radionuclide-contaminated soils and groundwater. When not trapped in the body, uranium poses little danger. In nature, uranium is found in all rocks and soils, and people can be exposed to innocuous amounts of uranium constantly (Langmuir, 1997). Health effects of uranium include impaired liver function and even cancer when ingested (EPA.gov). Uranium bioavailability is low when it enters the body initially; however, uranium in the form of the uranyl ion (UO_2^{2+}) is soluble and can be transported in the blood stream and accumulates in the kidneys and bones of both animals and humans (Neves et al., 2012; Carvalho, 2005).

The people of Laguna rely on the surface waters near their communities for irrigation, feeding livestock and for traditional uses (EIS-Vol. I, 1986). Water from the streams is not ingested directly by the pueblo, but plants, fish and livestock that use those waters are. Wind erosion of soils and sediments within and near the Rio Paguate and Rio San Jose means that most people see dust accumulating inside their homes and vehicles. There is a high chance that this dust also contains uranium.

In the study area, the landscape is dominated by the Mount Taylor volcanic field to the west and the canyons, mesas and volcanic necks of the Rio Puerco valley in the east. The Rio Puerco is the main drainage in this area. Major tributaries to the Rio Puerco include the Rio San Jose and the Rio Paguate which are the focus of this study. The Rio San Jose is a perennial stream while the Rio Paguate is an intermittent stream. Both streams, however, receive a large part of their annual flow from monsoonal moisture and are discussed in detail later.

2.2 Modern Landscape and Environment

2.2.1 Climate

The study area discussed here is part of the Laguna Indian Reservation approximately 45 miles from Albuquerque, New Mexico. Elevation of the study area ranges from 5600 feet in the riparian ecozone to about 6000 feet on basaltic mesas at the base of Mount Taylor (Dunmire, 1995). The climate is temperate and arid. Mean annual precipitation is around 9.07 inches (EIS, 1985). Winter temperatures are normally in the mid- 30's, while summer temperatures are in the 70's (EIS, 1985). Monsoonal rainfall and winter snowfall are the main sources of precipitation.

2.2.2 Drainages

The Laguna Mining District is part of the Rio Puerco drainage basin. The Rio San Jose is a major subbasin of the Rio Puerco with the Rio Paguate being a main tributary to the Rio San Jose (Popp et al., 1988). The Rio Puerco eventually drains into the Rio Grande. The Rio San Jose and the Rio Paguate are ephemeral streams. Stream valleys in the Laguna area are underlain by Jurassic sedimentary layers with diabase dikes and sills rising from the valley floor (Kittel et al., 1967).

2.2.2.1 Rio Paguate The Rio Paguate flows intermittently from the southeastern mesas of Mount Taylor, northwest of the Village of Paguate to its confluence with the Rio San Jose. The stream is fed with spring water and is perennial near its source and averages approximately 1 ft^3/second (Risser and Lyford, 1983) upstream of the village. In the Rio Paguate, water upstream from the mine is characterized as magnesium–bicarbonate type with a total dissolved solids (TDS) value of 600 mg/L. Below its confluence with the tributary, the Rio Moquino, within the mine, the water becomes a sodium-calcium-magnesium-sulfate type, and a TDS content of 1600 mg/L (EIS-Vol.I, 1986). In 1981, the waters within the mine showed a pH range from 7.4 to 8.5 (EIS-Vol I, 1986, p. 2-48). Higher elevation reaches of the Rio Paguate are vegetated with Gambel oak, birch, aspen, and juniper and pinon.

The Rio Paguate is diverted into Paguate Lake, a recreational fishing pond at Paguate (and above the mine). Near its source, the Rio Paguate is a straight stream until it reaches the relatively flat valley floor and becomes an arroyo with meandering and braided portions. Brandvold et al. (1981) report that the Rio Paguate was a permanent stream due to water being pumped from the uranium mines and discharged into the stream bed. Additional sources of water included flow from the Rio Moquino and groundwater discharge (Risser and Lyford, 1983). During the years 1976 to 1979, the flow at the Jackpile Mine averaged 1.3 ft^3/s (Risser and Lyford, 1983).

2.2.2.2 Rio San Jose The Rio San Jose is an entrenched braided river originating on the western side of Mount Taylor. It is fed by runoff from the western flanks of Mount Taylor, but mostly from Horace Springs near Seama, New Mexico. The flow at the Horace Springs is 5 ft^3/s and flows into the Rio Puerco. This drainage basin is thought to

have formed in late Oligocene time and was due to the subsidence of the Albuquerque Basin. The confluence with the Rio Puerco is approximately 6 miles south of Interstate 40 in the Suwanee Lava Flow. The Rio San Jose watershed is approximately 3745 mi^2 (Love, 1989). While it serves as a source of irrigation water for the Acoma and Laguna Pueblos, by the time it reaches the Village of Mesita, the Rio San Jose becomes an arroyo. The Rio San Jose at Mesita sits on a basalt flow that is 380,000±250,000 years old and overlies Rio San Jose valley fill (Hawley et al., 1982). The stream spans an elevation of 11,390 ft on top of Mount Taylor to the valley floor near Mesita at 5740 ft (O'Brien & Assoc., 1975).

2.2.3 Vegetation in the study area

Vegetation is comprised of perennial forbs and grasses, larger shrubs such as Russian olive, salt cedar and willows and stands of cattail. In some areas, larger trees such as cottonwoods may grow near the active stream. Salt cedars and Russian olives are invasive species that have established themselves in many river systems throughout New Mexico. The Rio San Jose and Rio Paguate are no exception. Every site, except for the higher altitude RPG02 site, has stands of salt cedar. This shrub prefers sandy or silty soils that have been created by flood events (Graf, 1999). The riparian communities of the lower Rio Paguate and Rio San Jose represent unstable vegetation that adjusts itself to changes in the river landscape (Graf, 1999). Every year is different in terms of precipitation, flow, and sediment load. These factors determine the dominant plant species in the community and have a profound effect in the uptake of uranium.

Willows prefer fine-grained sediments, tamarisk is less picky (Graf, 1999). Salt cedar is an "aggressive phreatophyte" meaning it puts out extensive taproots that seek water in the subsurface (Graf, 1999, p.102).

2.3 Geology

2.3.1 Regional Geology

The study area is part of the San Juan Basin and lies on the southeast edge of the Colorado Plateau (Nash, 1968) in northwest New Mexico (Figure 3).

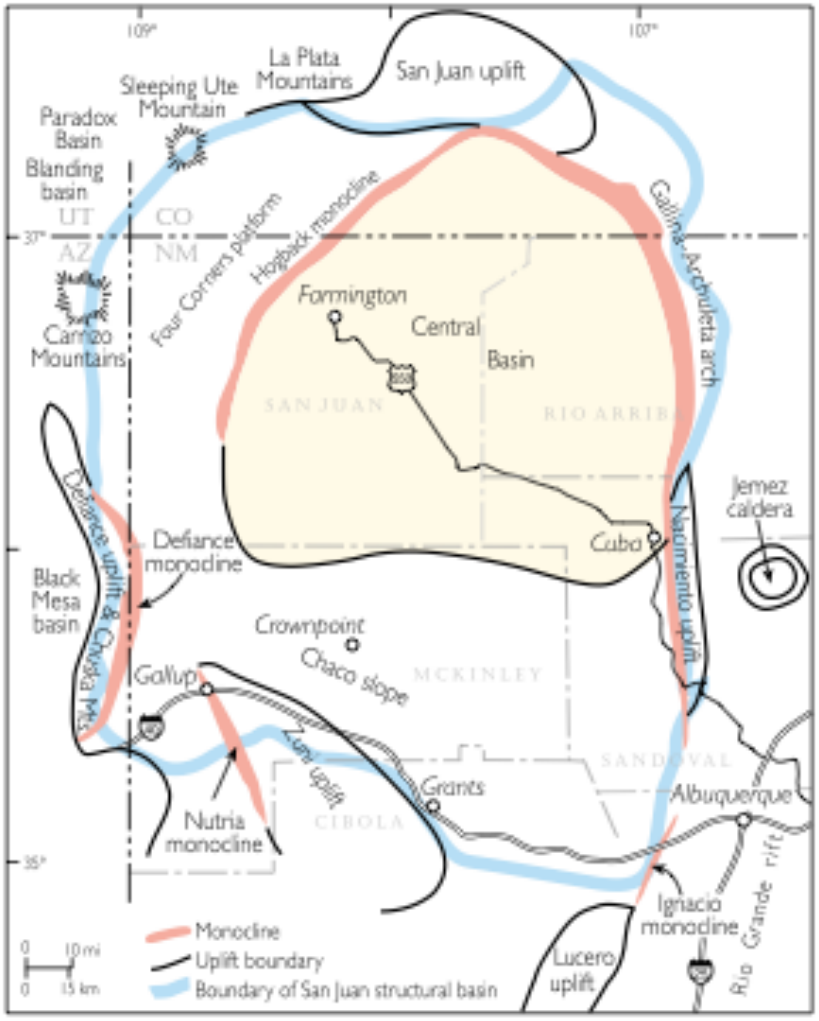


Figure 3. An overview of the San Juan Basin showing major geological features (DMFG, 2002, p. 22).

The San Juan Basin covers 26,000 miles within New Mexico and Colorado. Rocks within the Basin range in age from Pennsylvanian to Cretaceous (70 to 2 million years old) (Hilpert, 2963, p. 6). The San Juan Basin is a geographical area comprised of

monoclines which slope a number of geological formations inwards toward the center of the basin with the edges of the basin uplifted (Figure 4). The Basin is bordered to the east by Rio Grande trough which runs almost down the center of the entire state (Figure 3). The Chuska Mountains represent the western edge. The Acoma Sag and the Zuni Uplift mark the southern boundary of the San Juan Basin (Hilpert, 1963; DMFG, 2002). The stratigrapghy of the San Juan Basin is shown in Figure x. The sedimentary layers were deposited from about 330 to 2 Mya and represent the various depositional environments that have occurred in New Mexico from the Pennsylvanian through the Tertiary (DMFG, 2002, p.4). Of special significance because it pertains to this study is the Morrison Sandstone Formation, a Jurassic layer. This formation contains the Brushy Basin Sandstone Member of which the top layer is called the Jackpile Sandstone.

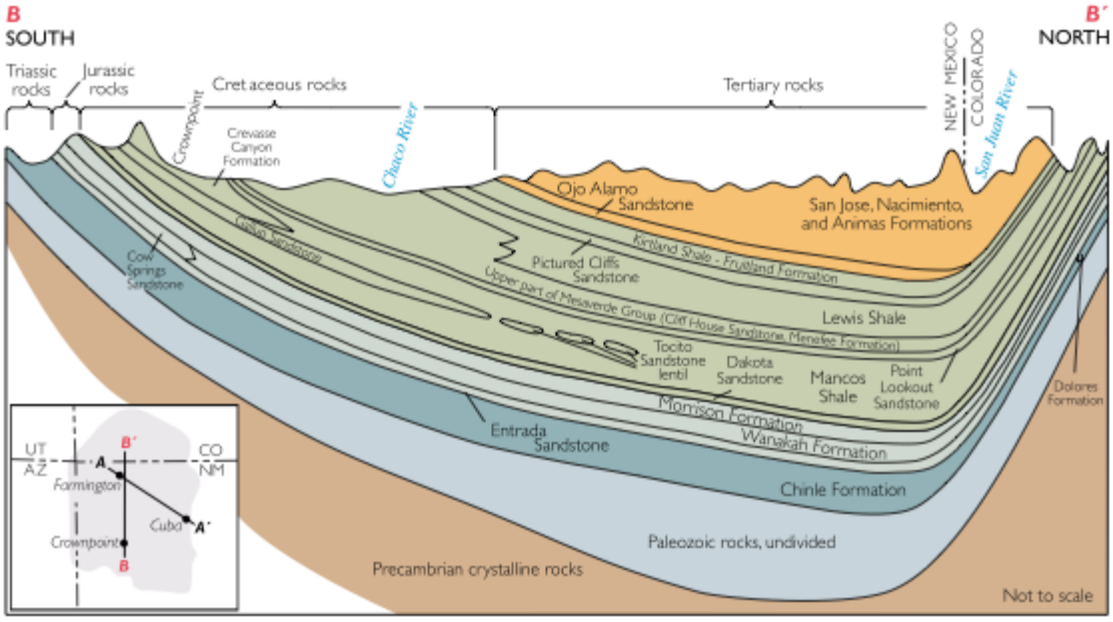


Figure 4. Cross-section of the San Juan Basin showing major lithologic units (DMFG, 2002, p. 23).

In the San Juan Basin the Morrison Formation has yielded most of the uranium mined in that area (Figure 5) (Nash, 1968). The Grants Mineral belt is positioned on the southern edge of the San Juan Basin where the Morrison Formation outcrops or else is near the surface. As of 2002, 97% of uranium from New Mexico was mined from the Grants Mineral Belt in the San Juan Basin.

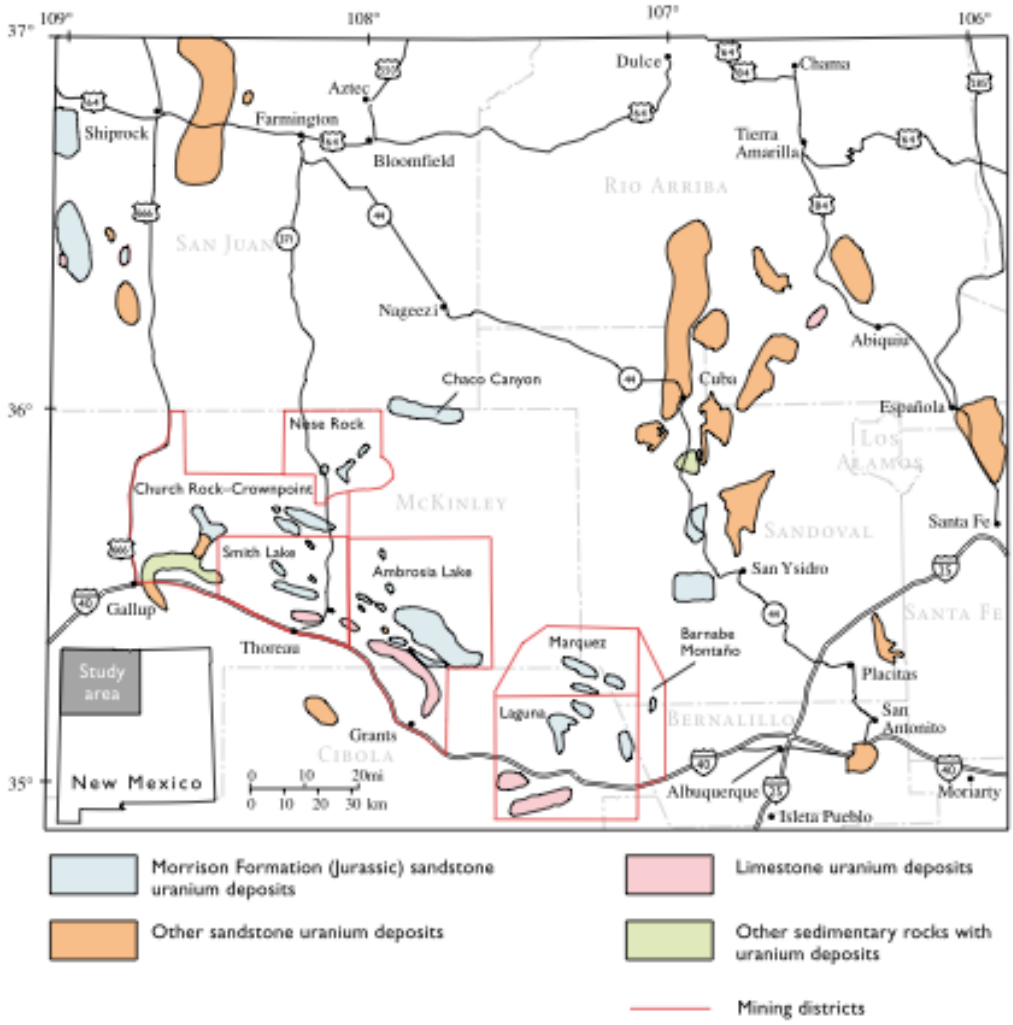


Figure 5. Map showing uranium deposits in the San Juan Basin (DMFG, 2002, p.32).

2.3.2 Local Geology

In the study area, the Morrison Formation is divided into three units: the Recapture Member, the Westwater Canyon Member and the Brushy Basin Member (Figure 6). Above this formation, in an angular unconformable contact, lies the Dakota Formation. It is comprised of the Mancos Shale and Tres Hermanos Sandstone. Below the Morrison Formation is the Bluff Sandstone, the Summerville Sandstone the Todilto Limestone and the Entrada Sandstone. The sandstones lie horizontally and almost flat, dipping slightly to the north-northwest by 2°, into the San Juan Basin. No major stratigraphic controls of the uranium deposits are noted (Beck et al., 1979).

The Jackpile sandstone bed is a sub-unit of the Brushy Basin Member, the youngest member of the Morrison Formation. The Jackpile Sandstone is made up of feldspar and quartz grains cemented with either calcite or clay, usually kaolinite. (Kittel, 1963; Moench & Schlee, 1967). The Brushy Basin Member is a gray, silty bentonitic mudstone while the lenses of Jackpile sandstone within it are commonly light gray or white due to the kaolinite. In areas where the Jackpile has been exposed for a considerable length of time, it takes on a yellowish color (Kittel, 1963). Grain size in the Jackpile Sandstone is comprised of fine to medium sand-sized particles of subangular to subrounded quartz and feldspar (Moench & Schlee, 1967; Kittel, 1963; Nash, 1968).

Uranium ore minerals in the Laguna District are found in the mainly in the Jackpile Sandstones and to a lesser extent in the Westwater Canyon Member of the Morrison Formation, the Todilto Formation and the Entrada Sandstone (Novo-Gradic, 1983; Moench, 1963). Granger (1963) explains that the uranium deposits in the Jackpile sandstone are elongated pods of sandstone cemented by uraniferous carbonaceous

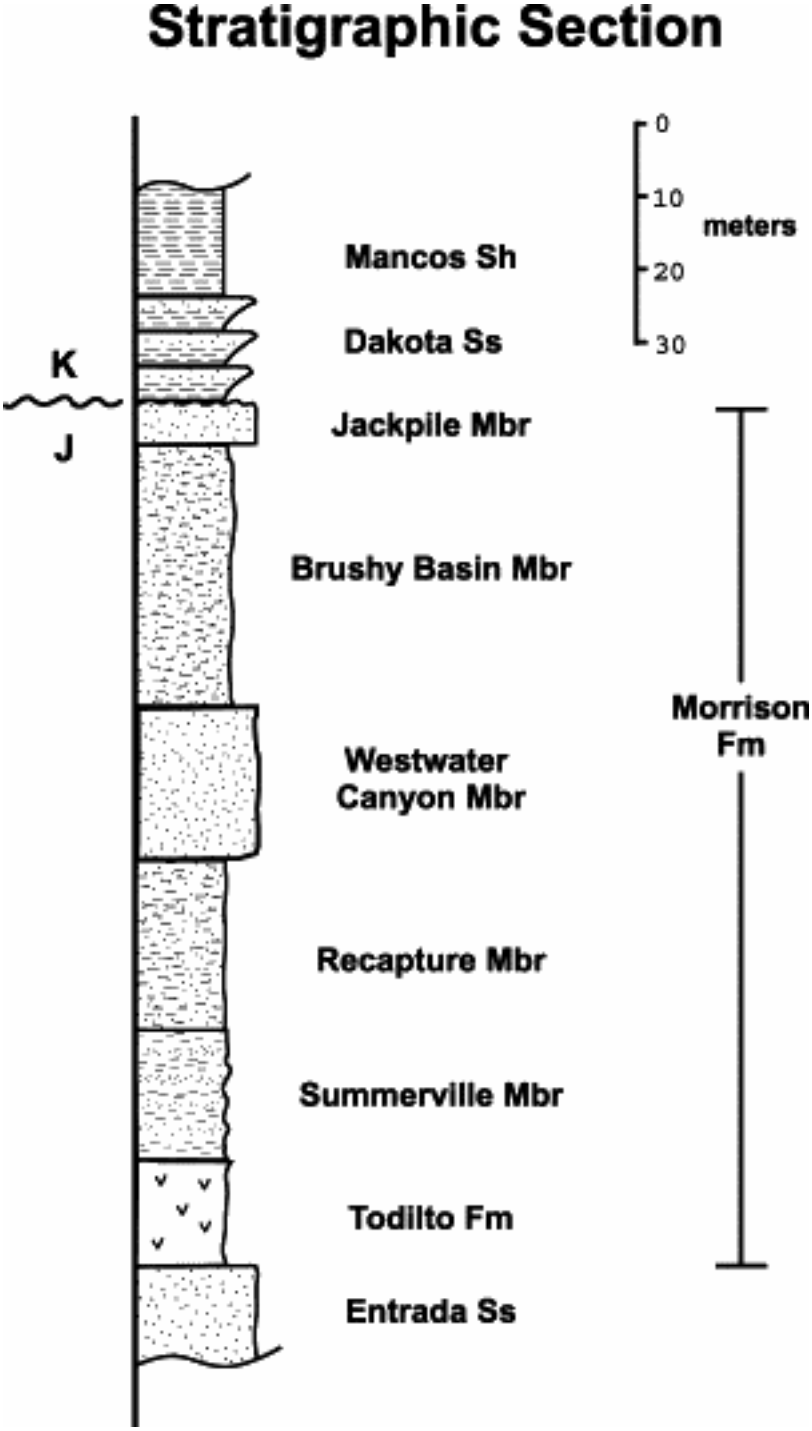


Figure 6. Local stratigraphy in the Laguna Mining District (Olsson et al, 2004, p. 327).

material. The uraniferous carbonaceous material is found in the humate masses that formed when vegetable trash filled stream channels and then was buried. It is thought

that the Jackpile sandstone covered a larger area, but was trimmed down by the erosion prior to the Dakota deposition (Moench & Schlee, 1967). The uranium deposits at the Jackpile Mine is discussed in more detail below.

The origin of the Morrison Formation including the Jackpile Sandstone is thought to be the Mogollon Highlands to the south from which streams deposited sediments onto a broad alluvial plain. The braided and meandering stream channels in this area would have stretched to the east, with fingers branching off to the south and north. The ore deposits in the Jackpile run in a northeasterly direction, indicative of the direction of drainage from the Mogollon Highlands (Beck et al., 1979). The tabular, elongate shape of the ore deposits are due to the accumulation of organic materials in the channels at the time of deposition. Minor folding of the area lead to a restriction of the streams to form a band 35 miles long, and approximately 15 miles wide (Kittel, 1963). The age of the sedimentation is approximately 146 mya (Beck et al., 1979).

A rubidium-strontium date of 113 mya has been determined for the formation of the uranium deposits , although this date does not take into account ore remobilization and reworking (Brookins, 1979). Other age indicators for the uranium deposits are diabase sills that are younger than than the Morrison Formation and cut through, displaced and metamorphosed the ore to a limited extent (Moench, 1963). It was once thought that these Tertiary-aged sills carried the uranium, because the sills are enriched in uranium. It was later concluded that the sills had become enriched by direct contact with the ore bearing sandstone (Nash, 1968).

The exact source of the uranium in the Jackpile Sandstone deposits is unknown. The Morrison Formation contains reworked volcanic ash, and the Jackpile Sandstone has

lenses of bentonite within it. It is believed that the uranium was leached out of the ash; however, the source or sources of the ash remains uncertain (Kittel, 1963). Groundwater from nearby volcanic mountains is another possible source of uranium. It is widely accepted that the uranium deposition occurred due to the meeting of two fluids at depth with differing chemical composition and oxidation-reduction states (McLemore, 2007).

Within the Jackpile Sandstone, the ore-containing horizon is up to 50 feet thick in some areas (Fitch, 1957). The thicker ore bodies correspond to areas of thicker Jackpile sandstone (Kittel, 1963). Vanadium, selenium and molybdenum have also been found in the Jackpile Sandstone within the Laguna Mining District, but not in economical quantities (Kittel, 1963). Coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$, is a common unoxidized mineral mined in the district, however, the ore is comprised of 2% coffinite, 15% uraninite, and the bulk is uranium complexes and unidentified uranium minerals (Kittel, 1963). The coffinite-uraninite mixture mined as ore is found in between quartz sand particles and even replaces feldspar and quartz grains (Granger, 1963). Darker rock indicates a higher ore grade, while a gray color can mean low-grade (Nash, 1968). The pods of humate are found in the similarly-shaped lenses of sandstone. These pods can be a few feet long to an acre and are suspended throughout the host sandstone (Moench, 1963). Due to the random and scattered occurrence of uranium-bearing humate pods, ore grade quality control is of utmost importance (Jackpot, 1978).

Other minerals found in the Jackpile Sandstone include zircon, tourmaline, garnet, rutile, hematite, magnetite and sillimanite. Biotite, amphiboles and pyroxenes are missing. This suite is unusual for arkosic sandstones, and probably arises from either

alteration of the sandstones or because “ferromagnesian minerals were not present in the source rocks” according to Nash (1968).

The Jackpile Sandstone serves as a source of uranium-laden sediments in the research area. To understand the mode of transport for uranium through the study area the geology of the Rio San Jose and Rio Paguate must be covered.

2.3.3 Jackpile Mine Area Geology

The Rio Paguate starts out in relatively young Tertiary-aged volcanics on Mt. Taylor. It then downcuts through the Cretaceous Mesaverde Group and Mancos Shale, the Dakota Sandstone, and the Morrison Sandstone Formation (Jurassic). Finally, it flows through Quaternary alluvials on its way to meet the Rio San Jose. (Figure 7).

The Rio San Jose starts out near Grants, NM. It flows mainly across Quaternary deposits near its source, then east over Dakota and the Morrison Formation sandstones near Laguna. Triassic sandstones of the Rock Point Formation are encountered as it crosses Interstate 40 to flow southeast then it flows through Quaternary alluvials on its way to the Rio Puerco (Figure 7). Both streams are ephemeral for the majority of their courses. Flow depends mainly on upstream use.

Volcanic rocks in the study area are basalts from the magmas that flowed from the Mount Taylor volcanic field. The tholeiitic basalts filling the Rio San Jose valley near Mesita are 380 my by K-Ar dating and overlies fine-grained alluvium (Hawley et al., 1982). The valley of the Rio San Jose had already been eroded 160-440 ft by the time the early Mt. Taylor basalts were erupted by 2.4 my (Love, 1989). A number of small volcanic necks also are found in the valleys. Sinkholes and pipes (collapse features) in Bluff and Summerville sandstone are exposed in the walls of mesas.

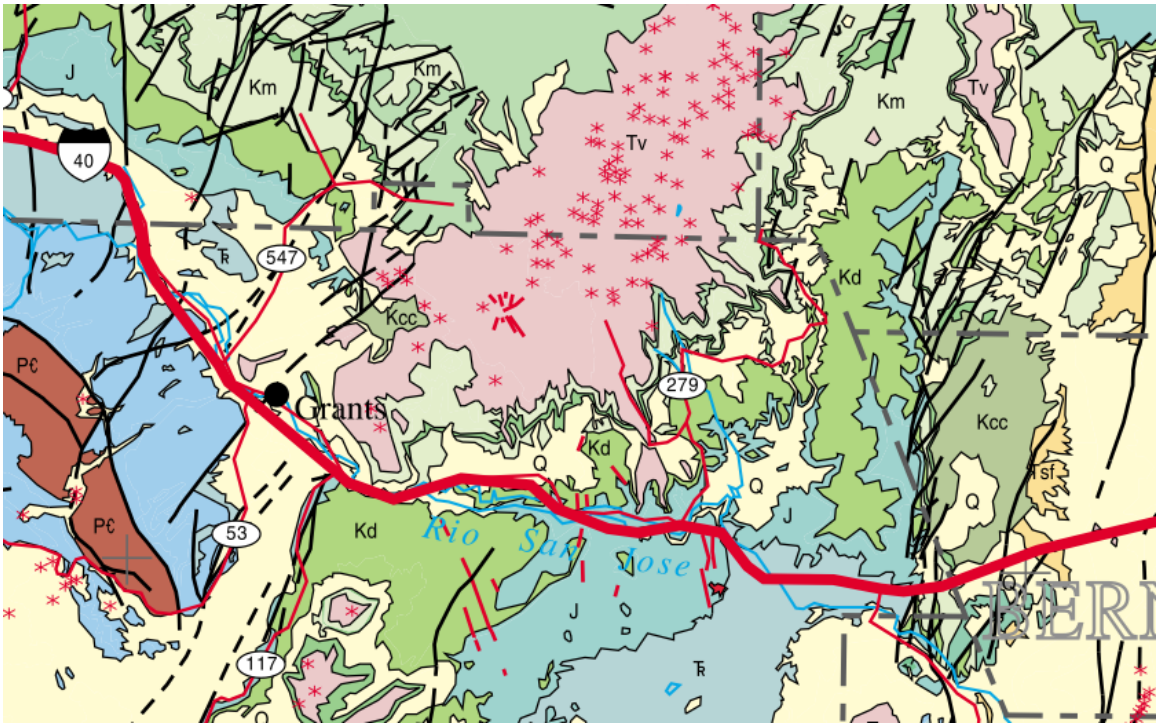


Figure 7. Major geologic units in the vicinity of the Rio San Jose and Rio Paguate (DMFG, 2002, p.153).

2.4 Uranium in the Environment

To understand the fate and transport of uranium in modern systems, it is necessary to understand the nature of the element, how uranium is deposited, how and where it occurs in nature, and its behavior under different chemical conditions. Uranium is a naturally occurring heavy element which undergoes radioactive decay (Langmuir, 1997). Radioactivity is a reaction that emits energy and heat as the element undergoes decay to reach a stable state. Figure 8 shows the isotopic decay for uranium 238 to lead 206. Energy being released from the nuclide creates daughter products, which include radon 222 which poses a threat to human health (Rautman, 1977). Natural concentrations of uranium include 2.2 to 15 µg/g in granites and 1.2 to 11.3 µg/g in sedimentary rocks

(Langmuir, 1997). Groundwater exposed to granites can contain up to 120 µg/L in uranium-enriched regions (Langmuir, 1997).

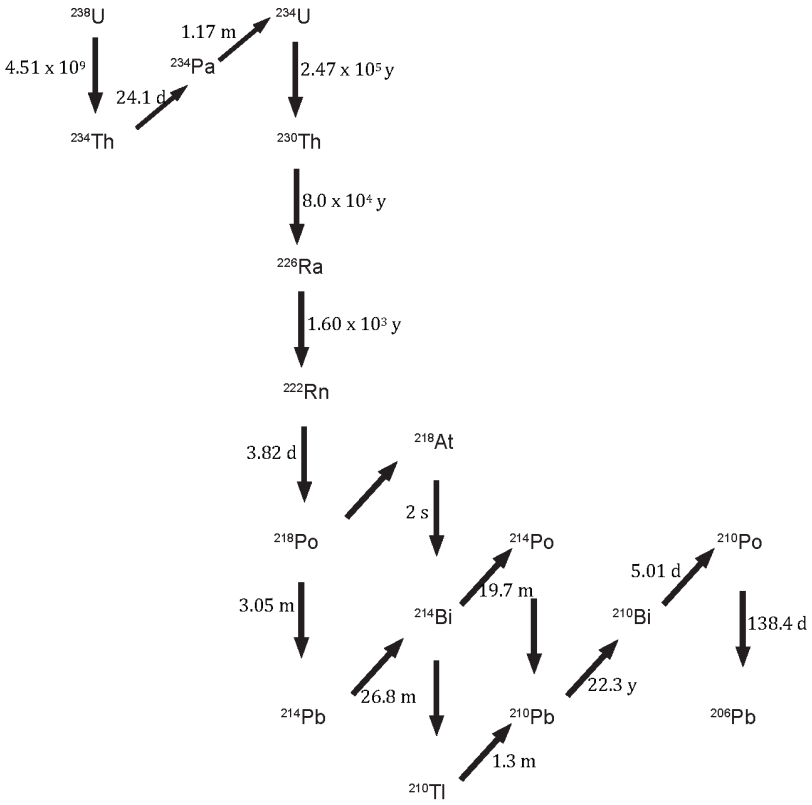


Figure 8. U-238 radiation decay series.

Concentrations of uranium and other heavy metals found in uranium ore deposits have been created by millions of years of groundwater flow. Uranium participates in redox reactions that mineralize mobile ions to immobile forms. The uranium remains mineralized as long as conditions remain suitable, but can easily be re-mobilizied.

Uranium is found in surface and ground waters in both uranous (U(IV)) and uranyl (U(VI)) oxidation states. Uranous, or tetravalent uranium U(IV), is the relatively insoluble reduced form which is easily oxidized to uranyl as conditions become more

oxidizing. Tetravalent uranium compounds are transported in colloidal form through surface and ground water (Brierly, 1981). Minerals incorporating U(IV) include uraninite (UO_2) and coffinite ($USiO_4$). These crystalline, "primary" minerals may be weathered and become oxidized over time.

Uranyl, or hexavalent uranium U(VI), is the soluble, oxidized form, although insoluble complexes with anions may also be formed. Neutral to alkaline natural waters typically have uranium carbonate complexes. Other common ions include chloride and sulfate. Minerals incorporating U(VI) include carnotite [$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$] and tyuyamunite [$Ca(UO_2)_2(VO_4)_2 \cdot 7\text{-}10.5H_2O$] (Langmuir, 1997; Moench, 1967). In acidic waters, U(VI) is present as uranyl cations (UO_2^{2+}). In alkaline waters, U (VI) is able to form complexes with dissolved carbonate that are soluble (Zielinski, 2008). Therefore, even in alkaline to neutral waters of the research area, uranium is found in the soluble, mobile form.

Uranium is most common in rocks that have been sourced from the mantle of the earth. Uranium can be introduced to the surface of the earth by volcanic activity or slow uplift and exposure. Uranium is found in silica-rich igneous rocks such as granites and from basic and acidic volcanics (Table 1). When exposed to groundwater, these intrusive rocks can weather physically and chemically releasing grains of uranium and thorium into the surrounding rocks. Extrusive rocks such as pumice and tuff can also contain uranium. Sandstones that have been created from sediments of igneous origin can have higher levels of uranium than sediments formed in other environments. In some instances, volcanic ash or tuff, enriched in uranium, is the prime stratigraphic layer from which uranium can disperse. With the introduction or groundwater flow, uranium in one

area is oxidized and then deposited in a reduced area. This type of secondary enrichment leads to uranium ore deposits, and is a result of redox reactions. This is called a roll-front deposit.

Table 1. Average uranium concentration in environment.

Rock Type	Uranium (ppm)	*Source*
Basalt (Crustal)	0.5-1	*Eisenbud & Gessel, 1997*
Mafic Basalt	0.5	*Eisenbud & Gessel, 1997*
Basic Igneous	0.6	*Eisenbud & Gessel, 1997*
Acid Igneous	3	*Eisenbud & Gessel, 1997*
Granite (Crustal)	3	*Eisenbud & Gessel, 1997*
Shale sandstones	3.7	*Eisenbud & Gessel, 1997*
Arkose	1-2	*Eisenbud & Gessel, 1997*
Carbonates	2	*Eisenbud & Gessel, 1997*
Continental Crust	2.8	*Eisenbud & Gessel, 1997*
Soil	1.8	*Eisenbud & Gessel, 1997*
High Grade Deposit	104-105	*Plant et al., 1999*
Low Grade Deposit	1000	*Ulmer-Scholle, 2012*
Groundwater	>0.001- 8	*Ulmer-Scholle, 2012*
Sea Water	0.003	*Ulmer-Scholle, 2012*

In shales, uranium ore deposits can form from other sedimentary strata with elevated concentrations of uranium due to groundwater mobilization followed by adsorption of uranium onto organics and clay minerals in the shale from other sedimentary strata with elevated concentrations of uranium (Langmuir, 1997). This type of uranium enrichment is called a uraniferous humate deposit.

Uranium pollution comes from human-caused activities and from exposure of naturally-occurring deposits through uplift and weathering. Uranium pollution usually involves transport in groundwater, surface water runoff, and/or by wind-blown dust. Anthropogenic causes of contamination of aquifers, streams and soils include leaking waste storage tanks and leaching ponds, improper waste disposal, and inadequate mining reclamation. Soil pollution poses a threat to human health because contaminants may be mobilized by erosion and groundwater flow (Eisenbud & Gessel, 1997).

2.4.1 Uranium Chemistry

Actinides, such as uranium, are strongly ionic meaning that when the actinide is dissolved in water, free ions of the actinide will form aquocomplexes with water through electrostatic and covalent forces (van Loon and Duffy, 2011). Ionic bond strength is related to the effective charge density of the metal ion. Uranium has a high bond strength as the free metal ion, UO^{2+}_2 (Choppin and Wong, 1998). In natural waters, other dissolved substances are present which may act as a ligand that attach to the actinide ion. This formation of a dissolved actinide and some other ion or molecule is termed a complex.

A complex can have characteristics and properties that the individual ions that comprise it do not. Ions found in natural waters are determined by the geology and chemical composition of the surrounding environment. Examples of ions include humic, carbonate and bicarbonate, sulfate, fluoride, chloride and perchlorate. For instance, the carbonate ion, HCO_3^- (aq), along with other carbonate species is often found in waters of the arid southwest. The addition of carbonate species can result in uranium species that

are soluble across a wider range of pH. Zielinski et al. (2008) found that at neutral to alkaline pHs, carbonate is the dominant ion and that uranium is present mainly as mobile uranyl carbonate complexes. This can be exploited on a large scale to extract uranium from ore and is called alkaline leach. The alkaline leach process mobilizes uranium by forming soluble uranyl carbonate complex at a high pH:

$$UO_2^{2+} + 2HCO^{3-} + CO_3^{2-} \rightarrow UO_2(CO_3)_3^{4-} + 2H^+$$

(Mason et al., 1997; Zielinski et al., 2008)

Uranium solubility is reliant on the oxidation state and the formation of complexes. Uranium is transported in surface water as the hexavalent uranyl ion, UO_2^{2+} and its complexes (Murphy and Shock, 1999). This ion is present in solutions with acidic pH (Ebbs et al., 1998). The waters in the study area can range in pH from approximately 7.5 to 8.5 (Novo-Gradac, 1983). In oxidized waters, such as surface and near-surface waters, U(VI) is the dominant ion. The soluble U(VI) is able to travel in solution but is then subject to a number of factors affecting its solubility, transport rate, precipitation and accumulation.

Near a pH value of 5, uranyl is a part of an aquocomplex. Near pH 6 or 7, the uranyl ions complex with carbonate species (Figure 9). When the uranium is not allowed to sorb onto organics in sandstones, the complexed ions will travel further to find the right conditions to cause precipitation (Langmuir, 1997). In general, dissolved uranium is comprised of uranyl ions complexed with chloride, sulfate and carbonate. The Rio Paguate and Rio San Jose are both considered alkaline water, as is the soil in this area, and contain carbonates. Examples of carbonate-uranium complexes that could be found in these streams include tricarbonate, $UO_2(CO_3)_3^{4-}$ and bicarbonate, $UO_2(CO_3)_2(H_2O)_3^{2-}$

(Brierly,1981). Under reducing conditions, U(IV) as UO^{2+} dominates, and in oxidizing conditions, U(VI) as UO_2^{2+} dominates (Figure 9). Increased concentration of carbonates increases solubility of uranium and limits adsorption to organic materials under oxidizing conditions.

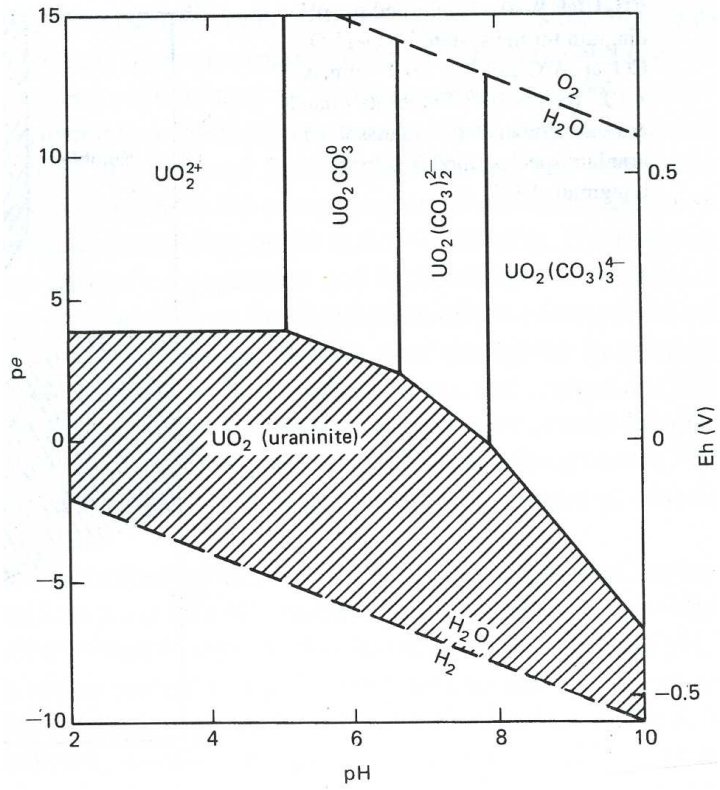


Figure 9. pe-pH diagram for U-O-H_2O-CO_2 system (Drever, 2002, p.).

Organic matter, both dissolved and particulate, in surface and ground waters also has an influence on the aqueous chemistry of uranium by forming complexes with uranium. As mentioned previously, interactions with the organic fulvic and humic acids is the way the uranium deposits of the Morrison Formation were created. Humic materials are a geopolymer able to complex metals through chelation, ion exchange and surface adsorption resulting in a stable metal humic complex (Brierly, 1981). These types

of complexes have the potential to interact with living organisms including vegetation by uptake of nutrients and trace metals.

2.4.2 Uranium Deposits in Humate

Situated in the youngest layers of the Morrison Formation, the Jackpile Sandstone hosts the uraniferous humate layers in pods and lenses. Through a combination of ion adsorption and reduction of uranium within irregular humate lenses, uranium is concentrated into ore (Guilbert, 2007). Uraniferous humate, or uranium-bearing humate, deposits are formed by the burial of large amounts of organic material causing reducing conditions in the sediments. A number of logs and even dinosaur bones managed to survive to modern times and are sometimes found in the course of mining. The logs and bones are often heavily enriched with uranium. Uranium content is directly related to the amount of organic carbon present in humate, but no other controls on ore grade and formation have been found (Beck et al., 1979). The organics decompose and reorganize into humate and infuse the immediate vicinity to create an acidic environment (humic acid). Humic acids, also called kerogen, dead oil or asphaltite, are released and aggregate or congeal into clumps (Nash, 1968). Groundwater carries uranium-sulfide ions and uranium-carbonate complexes from an oxidizing environment to a reducing environment. The ions are reduced from U^{6+} to U^{4+} by the humic acid and sulfate ions that were released into the surrounding sandstones. The humate also adsorbs uranyl ions from the uranium carbonates instead of just reducing them due to the high ion exchange capacity (Nash, 1968).

2.4.3 Sorption of Uranium to Sediments

The adsorption and transport of uranium to sediments allows for accumulation in stream sediments (Brierly, 1981). Rio San Jose and Rio Paguate water have a relatively high TDS content downstream of the Jackpile Mine and therefore has the potential to transport U adsorbed to sediments (Novo-Gradac, 1983.) Re-suspension of sediments and organic particles by wind and water is a principal process for transporting uranium (Whicker and Schultz, 1982, p. 132).

Streams with high sediment loads have the potential to carry more trace metals and actinides because metals can be adsorbed onto particulates in addition to being dissolved in the water. Brandvold et al. (1981) found that the total uranium in suspended sediment was much higher than the total uranium in filtered samples in the Rio San Jose. Sites studied in Brandvold et al include 2 sample locations on the Rio San Jose, near the Rio Paguate and one downstream of the Rio Paguate confluence. Although their study did not find a significant difference in dissolved trace metals between the mining areas and the Rio Grande at Bernardo, NM, suspended sediment yielded elevated uranium. With the high sediment loads of the Rio Paguate and Rio San Jose, uranium could be collecting on colloids or particulates and then settling out as soon as the energy environment allows.

Clays have a higher cation exchange capacity (CEC) than more coarse textured sands and clays. A study of CEC of sediments in some streams in the southwest found that clays had the highest CEC at ~42 meq/100g, silt had ~16meq/100g and sands had ~2.4 meq/100g (Novo-Gradac, 1983). Cation exchange occurs on sediment particles in

stream channels as well as suspended particles in the water. Adsorption to solids increases as the surface area per unit mass increases (Whicker and Schultz, 1982).

2.4.4 Possible Contamination Routes

Uranium mining and milling elsewhere in New Mexico has often led to the release of toxic materials into aquifers, surface streams and undisturbed or sensitive areas. Particulates carried by wind, and suspended and dissolved uranium in the streams can easily travel offsite to nearby communities. Reclamation efforts at Jackpile Mine are subject to wind erosion, storm runoff and seepage from ore piles and pits into underlying porous and permeable units. In a site inspection conducted by the U.S. Environmental Protection Agency in 2010, it was noted that surface water pathways were in direct contact with contaminated materials. The main sources of the contaminants were the waste dumps and pits.

2.4.4.1 Air Wind transportation is one way uranium can be redistributed. Wind erosion can re-transport contaminated sediments. These sediments can settle on vegetation or the uranium can be absorbed by the plants resulting in uranium entering the food stream. Wind erosion can transport sediments far from their original source.

Solubility of uranium determines its mobility and bioavailability in the environment. These two characteristics are integral in spreading uranium in the Rio San Jose and Rio Paguate drainages. Solubility and mobility are not just important concepts to understand on a larger stream-system scale, but also because solubility affects the bioavailability of uranium to plants which are the other large part of this study.

2.4.4.2 Vegetation Bioavailability is defined as the ability of a chemical compound to bind to or traverse the cell surface of an organism, including vegetation

(Markich, 2002). Therefore, bioavailability determines how much uranium a plant will take up. Uranium uptake by plants is usually limited to the dissolved fraction, implying that there may be less uranium available to plants if uranium is sorbed to sediments in the stream systems. The uranyl ion, which is soluble, is the plant-available form of U. Plants receive nutrients from the soil via the passage of ions from the soil solution into the roots, including the uranyl ion.

Uranium has somewhat low biological mobility because of its ability to form strong insoluble compounds; however, vegetation will absorb uranium under certain conditions such as low pH (Whicker and Schultz, 1982; Ebbs et al., 1998). In addition, surface deposition of uranium on leaves, stems and roots can occur (Whicker and Schultz, 1982). Some perennials can concentrate uranium to 100 ppm, especially when uranium concentration in the soil is high (Whicker and Schultz, 1982). When a plant which has accumulated uranium dies, seeds, leaves and stems are subject to transportation allowing for further contamination.

2.4.4.3 Surface Water The streams in the study area are major conveyors of sediments, and therefore uranium from the Jackpile Mine to the sample sites. Uranium may be transported in the Rio San Jose and Rio Paguate as dissolved or suspended solids. The Rio Paguate is able to mechanically transport grains of uranium ore offsite. As stated in section 2.4.3, the streams in the study area can also carry clays and fines which uranium can sorb on to in addition to dissolved uranyl ions present in the water.

2.5 The Jackpile Mine

The primary concern for uranium being transported in the Rio San Jose and Rio Paguate is due to the exposure of uranium rich deposits and ores at the surface during the history of mining at Jackpile Mine. To better understand the time scales of interest and possible sources, this next section provides background on the history of operations, and remediation efforts at Jackpile Mine.

2.5.1 *History of Mining in the Region*

Mining in the Grants Mineral Belt began in the 1950's and proceeded to become a booming industry through the mid-century (Table 2).

Uranium deposits of national economic importance in New Mexico were found in 1950 on land owned by the Santa Fe Railway Company (Boyle, 1976). After this major discovery of uranium in the Todilto Limestone at Haystack, New Mexico, northwest of Grants, Anaconda Copper Company started mining the deposits and, eventually, built a mill to handle the uranium-bearing limestone ore by carbonate leaching (Boyle, 1976; Smith, 1967). In search of further prospects, Anaconda began flying radiation detection instruments to find more uranium deposits in the area west of Mount Taylor where there were similar Todilto Limestone outcrops (Fitch, 1957). After this method proved disappointing, Anaconda began flying over the hills and arroyos on the Laguna Reservation, east and south of Mount Taylor. Prospecting using small aircraft with crews equipped with hand-held scintillometers and Geiger counters were a common way for companies to explore properties at the time (Hough, 1955; Kittel, 1963). The first step was airborne radiometric surveys, followed by land acquisition and exploratory drilling over hundreds of miles, and then more drilling within a tighter grid (Zimmermann, 1979,

Table 2. Events in the history of the Jackpile Mine.

Date	Event
1950	Santa Fe Railroad Company-Haystack Deposit found by Paddy Martinez [1]
Summer 1951	Anaconda Company flies airborne scintillation S. of Rt 66 and finds Todilto outcrops [1]
Fall 1951	Flights go north of Laguna and find the Jackpile outcrop, named Jack for the Anaconda manager at the time [1]
Late 1953	Isbell Construction Co. is contracted to begin stripping overburden to within 20 ft of the ore [1]
Early 1955	Isbell Construction Co. is again contracted to strip second, larger ore site N of Jackpile, the Paguate Deposit [1]
September 1955	Rail spur constructed off the Santa Fe main railroad line to Jackpile Mine [1]
Late 1955	The N and S pits are connected to help with ore handling [1]
Early 1956	Bluewater Mill completed to process Jackpile ore [1]
July 1980	Anaconda announces plan to phase-out open-pit mining immediately [2]
1982	Jackpile mine ceases operation due to uranium market conditions [3]
1986	Pueblo of Laguna, BLM, BIA and Anaconda/ARCO reach site clean-up agreement [4]
June 1995	Jackpile Reclamation Project completed [4]
September 2007	Record of Decision Compliance assessment for Jackpile determined that post-reclamation requirements had not been met [4]
Spring 2012	Jackpile is proposed to be Superfund site by the EPA [5]

Source

[1] Fitch, Herndon in Mining Congress Journal, June 1957, p. 57

[2] Hatchell, Wentz, Uranium Resources and Technology, 1980, p.59

[3] EPA EIS-Vol I, 1986

[4] EPA Site Narrative, accessed 3-14-12

[5] N.M. Mine, 2012

p. 12). The airborne prospecting was conducted under a leasing and prospecting agreement between Anaconda and the Laguna Tribal Council (Smith, 1967).

The initial deposit was 100 feet by 8.5 feet and contained 0.91% grade U_3O_8 as carnotite (Hough, 1955). The predominant form of uranium mineralization at Jackpile is coffinite and it occurs as near carbonaceous material, mudstone layers and bedding planes in the arkosic Jackpile Sandstone (Kittel, 1963). The Jackpile ore was not particularly high grade, but it was a reliable source. Anaconda began mining this particular outcrop, called the Jackpile Deposit, and later went on to develop the Paguate Deposit closer to the village of Paguate west of the Jackpile Deposit. The two deposits together comprised the Jackpile Mine.

While the Jackpile Mine was by far the largest and most important uranium mine in terms of size and production, the Laguna Mining District was home to a number of smaller mines, such as Woodrow, L-Bar, Saint Anthony and the Windwhip. A mill was located at Bibo, New Mexico, but was never put into full production by the time mining shutdown in 1980. According to a 1976 Report to the State Planning Officer concerning the Grants Mineral Belt, "in 1974, New Mexico produced 2,997,000 tons of uranium ore and 4,951 tons of uranium concentrate, 43 percent of the total United States production for that year." Until 1962, the main buyer of uranium was the Atomic Energy Commission (AEC) and used for defense purposes (Rautman, 1977).

2.5.3 The Jackpile Mine

The Jackpile Mine was originally leased under the location-patent system with the Bureau of Land Management in 1952, and was in full-scale production by 1956 (Hough, 1955). As Federal land, the lease was partially granted by both the Pueblo of Laguna and

the Bureau of Indian Affairs (Zimmermann, 1979). Anaconda leased 7500 acres of which 2800 acres were actively mined pits (Jackpot, 1978).

The mine site included infrastructure such as mine roads, access roads, office buildings and employee housing area and a railspur to take ore to the uranium mill in Bluewater, New Mexico. The mine employed around 400 miners and operators from the nearby villages comprising Laguna Pueblo.

The Jackpile mine was once the largest uranium mine in the world (Jackpot, 1978). Over a span of twenty-five years, the Grants Uranium Belt produced 55 million tons of ore. In 1977 alone, 14, 900 tons of yellow cake were produced in the United States, and 45% of that came out of the mines in New Mexico (Hoppe, 1978). The Jackpile Mine produced 6000 tons per day (tpd) at an average grade of 0.15% U_3O_8 from surface mines. As of 1978, 80 million lbs of yellowcake had been produced from the ore mined at Jackpile (Beck et al., 1980). From 1953 to 1978, 250 million tons of ore and waste had been excavated. Two underground portions produced 1300 tpd of 0.15% ore (Jackpot, 1978).

2.5.3 The Minesite

Initially, Anaconda planned to mine the Jackpile deposit by underground methods. Due to the location of diabase sills within the deposit, this was deemed impractical. In the end, surface mining methods were a safer option and would prevent the loss of up to 40% ore by collecting all of the overburden and ore (Fitch, 1957). In the areas closest to the diabase sills, mining was performed with jackhammers to prevent any of the igneous rock from contaminating the ore and fouling mill operations (Fitch, 1957).

The cutoff grade was 0.04% U_3O_8 in 1978 (Jackpot, 1978). Uranium was mined from three open pits and nine underground mines.

In order to reach the ore-bearing horizons, about 100 feet of overburden had to be removed by means of blasting with ANFO (or dynamite in the early days) and then cleared with shovels and bulldozers in a manner similar to surface coal mining (Fitch, 1957). Mining was performed to control ore grade as much as possible. Exploration drilling used a tight grid of 50 x 50 feet. Blast holes were probed with a scintillometer. When the ore horizon was exposed after blasting and overburden removal, the ripped area was then surveyed to delineate the ore, and grades of ore were "flagged" for selective mining. Dump trucks were front-end loaded with the ore and sent through a gamma-beta counter from which trucks were sent to the corresponding grade stockpile. Before being sent to the crusher and load-out, the ore was again checked with a scintillometer so that the mill at Bluewater would know what grade of ore it was receiving in each of the thirty 100-ton capacity train cars. The Jackpile and Paguate pits combined to become a single large pit that was three miles long and up to 500 feet wide, and 300 feet deep (Jackpot, 1978). Almost 3 million tons of material including overburden and waste was moved per month (Jackpot, 1978)

In 1955, a rail spur was added that directly linked the Jackpile mine with the main railroad line 5 miles south of the mine site (Fitch, 1957). The uranium processing mill at Bluewater, New Mexico, was built to process the Jackpile ore into yellowcake. The road to the Jackpile Mine from U.S. 66 was constructed by the AEC in 1953 (Smith, 1967).

The Jackpile Mine was closed in 1983 after uranium market prices could no longer sustain the mining operation. With the cessation of production, emphasis shifted to

the reclamation and revegetation of the pits and disturbed areas. The Pueblo of Laguna was tasked with spearheading the reclamation through the Laguna Construction Inc., working as a contractor for Anaconda Minerals, which was by bought by ARCO Oil and Gas in 1977. To date, reclamation work totaling approximately 43 million dollars has been completed, and today the mine site still consists of partially filled pits (pers. commun., V. Sarracino). Reclamation and revegetation is minimal (pers. commun., C. Francisco).

Information regarding mining practices and reclamation procedures at Jackpile Mine are available through the Department of the Interior Bureau of Indian Affairs (BIA) which retains documents relating to the leasing agreements as well as information pertaining to the reclamation and closure of the mine. The University of Wyoming American Heritage Center has the Anaconda Collection that contains paperwork and documents originating from Anaconda Minerals regarding the mine. Also, the Bureau of Land Management, which participated in the closure of the mine, has information about the mine reclamation.

2.5.4 Previous Site Remediation

While the Jackpile Mine ceased production in 1983, a reclamation agreement between Anaconda Minerals Company, the Bureau of Land Management (BLM), the Bureau of Indian Affairs (BIA) and the Tribe of Laguna was not reached until 1986. According to the Record of Decision from the BLM and BIA, the estimated cost of reclamation was approximately 43 million dollars to be paid by Anaconda from its $45 million bond held by the BLM (NROD, 1986).

Anaconda itself performed little reclamation, and in 1987, Laguna Pueblo contracted Jacobs Engineering of Albuquerque, New Mexico, to manage the reclamation project. Earthwork and heavy-machinery operations were performed by the tribal-owned Laguna Construction Company.

The reclamation plan outlined three types of work that needed to be done to improve the land-use possibilities and inhibit any sediments and particulates from travelling off-site: radiological protection, reclamation of pits and dumps and revegetation of disturbed acreage. Radiological concerns stemmed from the protore, or ore of low uranium content, piles that emitted radon daughters. These materials were buried as backfill for the pits and topped with at least three feet of Mancos shale and two feet of soil. This reduced the amount of radon being emitted to less than 3 pCi/L.

In addition to the protore and the waste piles of overburden being used as backfill, soil salvaged from the vicinity was also used. The highwalls were then cut to a 1:1 slope near the top, and then a fence was installed around the perimeter. The Rio Moquino, a tributary of the Rio Paguate, was rerouted to flow 50 feet away from nearby waste dumps. Water in the bottom of the pits was deemed to be not contaminated enough to need to be treated, and it was expected that after pit dewatering the remaining sediments would be buried by the reclamation activities and therefore not pose a hazard (Reith et al., 1993). The pits were dewatered, and then filled in with protore as described above.

Revegetation was a challenge due to the scarcity of suitable topdressing soil. Tres Hermanos sandstone was used for topsoil when necessary. When crushed to a coarse gravel, the sandstone provided a rough seedbed that was shown to grow the seedmix of rangeland vegetation (Appendix 1) (Reith et al., 1993).

The reclamation performed at the Jackpile mine was "the first attempt in the world to reclaim an open pit uranium mine … the Pueblo continues to monitor the mine and its ongoing impacts." (Luarkie, 2012). In 2007, an assessment of the conditions of the Record of Decision (ROD) was conducted. Based on the success of the revegetation and other non-compliant issues, it was determined that the reclamation of the minesite was lacking (EPA, 2012). Reclamation of mine sites poses many challenges, especially in semi-arid and arid regions (Kelley, 1979). Currently, the Pueblo of Laguna Environmental and Natural Resources Department is sampling surface water for trace analysis including metals. Additional analyses of the water, soil and especially vegetation would give the tribe a better understanding of the extent of uranium mobilization on their lands.

2.6 Previous Studies

Previous work at the site on the uranium deposits in the Laguna Mining District include resource exploration, geology and environmental impact reports from the 1980's and earlier. In the 1950s and 60s, the area was the new frontier for uranium exploration in New Mexico. As the industry grew, the need for an understanding of the environmental impacts of mining and milling became more important. Research into heavy metal concentrations in the Rio Puerco, Rio San Jose and the Puerco River of the west were conducted in the 1970s and 1980s (Popp et al, 1988; Miller 1986; Brandvold et al, 1981. The researchers established levels of background uranium concentration in the Grants Mineral belt. During active mining, it was a common practice to send water pumped from mines to the major streams of the region, such as San Mateo Creek and the Rio Paguate,

both of which drained to the Rio San Jose and on into the Rio Grande. It was determined that heavy metal background concentrations were identified in the oxbow sediments of the Rio Puerco that were deposited prior to uranium mine activity (Popp et al., 1988). Studies concerning the Rio San Jose itself are not as numerous. Novo-Gradac (1983) focused on the Rio Puerco in his Master's Thesis, but took into account the role of the Rio San Jose and Rio Paguate sediments in transporting heavy metals as well.

Similar research has also been conducted on the western Rio Puerco that drains the western part of the Grants Mineral Belt. A disastrous 1979 dam breach sent 3.5 million cubic meters of uranium mine wastes into the Puerco River at the United Nuclear Corporation Churchrock mill near Gallup, New Mexico (Miller & Wells, 1986). This study identified three major contaminant and sediment storage sites in the following geomorphic features: floodplain, bankfull channel and tributary-backwater deposits. The authors also concluded that contamination was hard to detect at the time of their study and was due to dilution and sediment reworking.

CHAPTER 3

METHODS

3.1 Sampling Sites

Sampling had to be performed under the supervision of Laguna Pueblo personnel. For each sampling trip, Curtis Francisco and Dorothy Beecher of the Laguna Environmental Department would drive out to sites and assist with sample collection. The department is responsible for water and sediment sampling along the Rio Paguate and Rio San Jose for monitoring purposes. Sample locations and dates are shown in Table 3.

3.3 Sample Site Selection

Sample sites were chosen based on ease of access, adequate vegetation growth to provide vegetation samples and standing pools of water after precipitation events. All sites had adequate soil cover to ensure that soil samples could be obtained at 12 inches deep.

Two of the sites therefore are located at dams, one on the Rio Paguate and one on the Rio San Jose downstream of any mining activity. Two background sites were chosen that were upstream of mining activity within the Laguna Mining District. The first

background site (RSJB) is upstream of any uranium mining and milling activity from the Laguna District on the Rio San Jose and is located near the village of Casa Blanca. It is also upstream of the Village of Laguna's wastewater effluent source. The second background site (RPG02) is on the Rio Paguate on the slopes of Mount Taylor. The other three sites consist of the Rio Paguate where it exits the Jackpile Mine site (RPG03), the Rio Paguate at the Paguate Reservoir before it joins the Rio San Jose (RPG04), and the Rio San Jose near the village of Mesita downstream of the confluence with the Rio Paguate and co-located with the Mesita irrigation diversion (RSJ06). The locations of the sites are shown in Figure 1. Sample names consist of the site name and date collected followed by a single digit, usually reflective of the order in which the plant sample was collected that day.

The sites were chosen based upon the sampling scheme that the Laguna Environmental Department uses for their Clean Water Act (CWA) compliance monitoring.

A few challenges were encountered during soil and plant sampling, including inadequate amounts of plant species due to the drought during the study period, hard to obtain soil and access to sampling sites. The Paguate Reservoir was one site when vegetation was not abundant, or was abundant in different areas at different times of the year depending on the amount of water behind the dam. In the case of the samples collected on October 25, 2011, Paguate Reservoir was completely under water. Although cattails were growing in the water, there was not a safe way to collect them. Samples were then collected from an area downstream of the dam that was receiving water. The

Table 3. List of all sampling sites and dates visited.

Sample Site	Location		Comments	Sample Collection Dates				
	Longitude	Latitude		August 19 2009	July 22 2010	September 15 2010	June 1 2011	October 25 2011
RPG02	107°19'37.25" W	35°1'25.081" N	Rio Paguate Background	Not visited	Plants	Plants, soils, water	Plants, soils	Not visited
RPG03	107° 28' 30.235" W	35° 2' 49.978" N	Rio Paguate at the exit of the Jackpile mine	Not visited	Plants	Plants, soils, water	Plants, soils	Plants
RPG04	107° 19' 58.320" W	35° 4' 23.851" N	Rio Paguate at the Paguate Reservoir and channel into the reservoir	Soils, plants, water	Plants	Plants, soils, water	Plants, soils	Plants
RSJB	107° 20' 11.431" W	35° 7' 23.874" N	Rio San Jose Background near Casa Blanca, NM	Not visited	Plants	Plants, soils, water	Plants, soils	Plants
RSJ06	107° 25' 56.683" W	35° 9' 34.950" N	Rio San Jose at the Mesita diversion near Mesita NM	Soils, plants, water	Plants	Plants, soils, water	Plants, soils	Plants

plants that were taken from this area were plants that liked water and could grow on the sandstone ledges there. At other times, there was no water at all coming into the reservoir and no plants growing in the area. During the summer of 2011, even the salt cedars were showing signs of distress from the drought. The RPG04 channel never provided any vegetation. The area was chosen because it has a good delineated channel not found closer to the dam at Paguate Reservoir. This area is mostly sand with a crust of shaley sediment that grows salt cedars and low grasses in a scattered interspersed way near the channel itself. Plant samples representing the Rio Paguate-Paguate Reservoir area were taken from behind the dam where larger, more developed specimens could be gathered.

For the Rio San Jose background site, the area was disturbed by the construction of a bridge that limited the soil samples to the channel primarily, and the south bank that still had been moved fairly recently, but was less disturbed than the other areas. Plant samples were mainly gathered from the channel. The Rio San Jose at this site near Casa Blanca is a dry arroyo and a rather steep-sided deep channel.

Soil samples from the Rio Paguate background were also problematic because of the very rocky soil. This site had a stony layer under about 8 inches of soil. For this reason, the 6-12” soil sample was not collected during the September 15, 2010 trip.

3.4 Sampling Procedure In The Field

Sample sites were made up of a transect across the site’s stream bed. Plants, soils and water were then collected across a transect. For the site at the Paguate Reservoir

(RPG04), soil and vegetation samples were taken from the near-shore vicinity. During one sampling trip, the water in the reservoir was high, and it was not possible to collect plant samples from the regular site. Downstream of the dam were small rivulets and pools of water. Plants were gathered from out of this water. As often as possible, the same type of vegetation was gathered from the different sites. Common plants were tumbleweed, koscia, salt cedar and Russian olive. A complete list of plants is given in Table 4. Plants with a question mark after are plants that were not positively identified. Forbs were pulled out by the roots and shaken to get any loose soil off. Branches were cut from large shrubs and trees.

Soil samples were collected by digging a 12-inch (30.48 cm) hole and scraping the sides at 6 inches and 12 inches into a plastic bag. These pits were dug on either side of a stream channel and in the channel when possible along a transect.

Water samples were obtained with a peristaltic pump. Field pH and conductivity readings were taken. Samples were kept cool (4° C) until return to the New Mexico Bureau of Geology and Mineral Resource's chemistry lab in Socorro, New Mexico.

Table 4. List of plants collected from study area.

Sample Name	Common Name	Scientific Name
RPG04-0809-1	Aster daisy	*Dieterea*
RPG04-0809-2	Cattail	*Typha latifolia*
RPG04-0809-3	Sedge	*Cyperacaea*
RPG04-0809-4	Common Reed	*Phragmites communis*
RPG04-0809-5	Russian Olive olives	*Elaeagnus angustifolia*
RPG04-0809-5A	Russian Olives (leaves)	*Elaeagnus angustifolia*
RPG04-0809-6	Salt Cedar	*Tamarix*
RPG04-0809-7	Salt Cedar	*Tamarix*
RSJ06-0809-1	Tumbleweed	*Salsola tragus*
RSJ06-0809-2	Bullrush	*Scirpus acutus*
RSJ06-0809-3	Salt Cedar	*Tamarix*
RSJ06-0809-4	White clover	*Melilotus albus*
RSJ06-0809-5	Amaranth	*Amaranthus retroflexus*
RSJ06-0809-6	Sunflower	*Helianthus annuus*
RSJ06-0809-7	Amaranth	*Amaranthus retroflexus*
RSJ06-0809-8	Cattail	*Typha latifolia*
RSJ06-0809-9	Baby salt cedar	*Tamarix*
RSJ06-0809-10	Prickly Lettuce	*Lactuca serriola*
RSJ06-0809-11	Milo	*Sorghum*
RSJ06-0809-12	Milo on fill	*Sorghum*
RSJ06-0809-13	Globemallow	*Sphaeralcea fendleri*
RSJ06-0809-14	Young tumbleweed	*Salsola tragus*
RSJ06-0809-15	Koscia	*Kochia scoparia*
RSJ06-0809-16	Mares Tail	*Conyza canadensis*
RPG02-72210-1	Alder	*Alnus*
RPG02-72210-2	Oatgrass	*Arrhenatherum elatius*
RPG02-72210-3	Common mullein	*Verbascum thapsus*
RPG02-72210-4	Watercress	*Nasturtium officinale*
RPG02-72210-5	Unidentified grass	
RPG02-72210-6	Red Plantain	*Plantago atropurpurea*
RPG03-72210-7	Cattail	*Typha latifolia*
RPG03-72210-8	Salt Cedar	*Tamarix*
RPG03-72210-9	White Clover	*Melilotus albus*
RPG03-72210-10	Russian Olive	*Elaeagnus angustifolia*
RPG04-72210-11	Cattail	*Typha latifolia*
RPG04-72210-12	Russian Olive	*Elaeagnus angustifolia*
RPG04-72210-13	Salt Cedar	*Tamarix*
RPG04-72210-14	Unidentified Rush	
RSJ06-72210-15	Russian Olive	*Elaeagnus angustifolia*
RSJ06-72210-16	Cocklebur	*Xanthium strumarium*
RSJ06-72210-17	White Clover	*Melilotus albus*
RSJ06-72210-18	Salt Cedar	*Tamarix*
RSJ06-72210-19	Tumbleweed	*Salsola tragus*
RSJB-72210-20	Salt Cedar	*Tamarix*
RSJB-72210-21	Russian Olive	*Elaeagnus angustifolia*
RSJB-72210-22	Common Reed	*Phragmites communis*
RSJB-72210-23	Cocklebur	*Xanthium strumarium*
RSJB-72210-24	Kochia	*Kochia scoparia*

Table 4. -Continued

RPG02-6111-1	Clover	*Melilotus albus*
RPG02-6111-2	Bentgrass (?)	*Agrostis stolonifera*
RPG02-6111-3	Bluegrass (?)	*Poa fendleriana*
RPG02-6111-4	Meadowrue	*Thalictrum fendleri*
RPG02-6111-5	Cutleaf coneflower	*Rudbeckia laciniata*
RPG02-6111-6	Spotted water hemlock	*Cicuta maculata*
RPG03-6111-7	Young vine mesquite	*Panicum obtusum*
RPG03-6111-8	Kochia	*Kochia scoparia*
RPG03-6111-9	White clover	*Melilotus albus*
RPG03-6111-10	Russian olive	*Elaeagnus angustifolia*
RPG03-6111-11	Young salt cedar	*Tamarix petandra*
RPG03-6111-12	Bullrush	*Scirpus acutus*
RPG03-6111-13	Cattail	*Typha latifolia*
RRSJ06-6111-14	Amaranth (bank)	*Amaranthus retroflexus*
RRSJ06-6111-15	Amaranth (channel)	*Amaranthus retroflexus*
RRSJ06-6111-16	Slender wheatgrass/Arizona fescue (?)	
RRSJ06-6111-17	Russian olive	*Elaeagnus angustifolia*
RRSJ06-6111-18	Squirreltail	*Elymus elymoides*
RRSJ06-6111-19	Young salt cedar	*Tamarix*
RSJB-6111-20	Sacoton (?)	*Sporobolus giganteus?*
RSJB-6111-21	Bullrush	*Scirpus acutus*
RSJB-6111-22	Wooly plantain	*Plantago patagonica*
RSJB-6111-23	Cottonwood	*Populus angustifolia*
RSJB-6111-24	Kochia	*Kochia scoparia*
RSJB-6111-25	Young tumbleweed	*Salsola tragus*
RSJB-6111-26	Japanese brome	*Bromus japonicus*
RSJB-6111-27	Western wheatgrass	*Elymus smithii*
RSJB-6111-28	Squirreltail	*Elymus elymoides*
RSJB-6111-29	Unidentified phlox	
RSJB-6111-30	Wild lettuce	*Letuca virosa*
RSJB-102511-1	Curly dock (?)	*Rumex*
RSJB-102511-2	Kochia	*Kochia scoparia*
RSJB-102511-3	Willow	*Salix exigna*
RSJB-102511-4	Cottonwood	*Populus angustifolia*
RSJB-102511-5	Western wheatgrass (?)	
RSJB-102511-6	Sand dropseed (?)	
RPG03-102511-7	Willow	*Salix exigna*
RPG03-102511-8	Rabbitbush	*Ericameria nauseosa*
RPG03-102511-9	Cattails	*Typha latifolia*
RPG03-102511-10	White Clover	*Melilotus albus*
RPG04-102511-11	Prickly Lettuce (?)	*Lactuca serriola*
RPG04-102511-12	Underwater grass?	
RPG04-102511-13	Cattails	*Typha latifolia*
RPG04-102511-14	Great Plantain	*Plantago*
RSJ06-102511-15	Salt cedar	*Tamarix*
RSJ06-102511-16	Tumbleweed	*Salsola tragus*
RSJ06-102511-17	Cockleburr	*Xanthium strumarium*
RSJ06-102511-18	Russian olive	*Elaeagnus angustifolia*
RSJ06-102511-19	Four-wing Saltbush	*Atriplex canescens*

3.5 Sample Preparation and Digestion

Vegetation samples were carefully rinsed, washed and rinsed again in reverse osmosis water then left to air dry completely. The samples were then ground in a small coffee grinder (Mr. Coffee Model IDS55, 120V, 60Hz, 130W and Model IDS50, 120V, 60Hz, 90W), sieved to the less than 2-mm fraction and then passed through a riffle splitter with 1.27 cm openings. Any pebbles, roots, leaves or twigs were removed. Of the two splits, one was taken and oven-dried at 75 °C for at least 8 hours or overnight to become the sample that would be analyzed.

The soil samples that were damp or wet, were dried. Chunks of clay were chipped off and ground enough to fit through a riffle splitter with 3-mm openings. One split was sieved through a No. 10 sieve. Any piece not able to pass through the sieve was ground fine with a mortar and pestle. This sieved split was then oven-dried at 75 °C for 8 hours or, overnight. This portion was used in microwave digestions.

In preparation for pipette analysis of fines, the remaining sample was sieved using a riffle splitter with 1.27 cm openings. Any large clods were broken up until they could pass through the splitter openings. A split was then bagged and used for the pipette tests.

Water samples were kept in a refrigerator at about 5°C, analyzed for pH and conductivity, and then run through the optical emission spectrometry-mass spectrometer to obtain Fe concentration.

3.5.1 Microwave digestion procedure

Both soil and vegetation samples had to be digested. Due to the amount of silica in grasses, initially a hydrofluoric acid method was used. After comparison between this method and a process using nitric acid and hydrogen peroxide, it was decided that the

hydrofluoric acid did not provide a more complete extraction of uranium from the vegetation.

For every 0.2 to 0.25 grams of soil sample, 8.00 mL of nitric acid (HNO3), 10.00 mL of RO and 3.00 mL of hydrochloric acid (HCl (aq)) were added to a sterile sealable Teflon microwave vessel (Milestone Inc., Monroe, CT). The vessels are capped and sealed with a torque wrench. The vessels were then positioned on a rotating plate in the microwave (Milestone Inc.). The microwave program used was titled 'NMT Soils 195.' The program raises the temperature to 210°C over 10 minutes, then holds that temperature for 15 minutes followed by a cooling period of 40 minutes. The vessels are then removed from the microwave and allowed to cool to room temperature, usually overnight. When the vessels are opened, the solution is filtered using Whatman No. 4 filters into a 50-mL plastic vessel. The solution is brought to 50-mL volume. Dilutions were usually made to 1:10 by adding 9.00 mL of RO water to a vial and then adding 1000 μL of sample.

Plant samples weighing between 0.2 and 0.25 grams were added to sterile sealable Teflon vessels. To this was added 5.00 mL of trace metal grade nitric acid (HNO^3) , 2.00 mL of 30% hydrogen peroxide (H_2O_2), and 5.00 mL of RO water. The vessels were capped and secured as described for the soils and place in the microwave. The microwave program used for these began with heating up to 85°C over 2 minutes; to 145°C over 5 minutes, holding a constant temperature of 210°C for 20 minutes followed by a cooling for 20 minutes.

3.6 Mass Spectrometry Analysis

Inductively coupled plasma mass spectrometry (ICP-MS) analysis was carried out in the Chemistry Laboratory at the New Mexico Bureau of Geology and Mineral Resources. The ICP-MS (Agilent 7500i Inductively Coupled Plasma Mass Spectrometer) was used to measure the amount of uranium in plants and soil particles. The ICP-MS utilizes the Chemstation program (Agilent Technologies, 1999) to measure the uranium as μg in liter of solution which is then converted to parts per million (ppm), or mg uranium per kg of sample based on the initital dry weight of sample prior to analyses using the following formula:

U (in mg/kg) = (uranium concentration in μg/L) * (50 mL/dry weight in grams) * (1L/1000 mL) * (1mg/1000 μg) * (1000g/1kg)

3.7 Particle Size Analyses

Soil particle size was determined by pipette analysis in the soils laboratory in the Earth and Environmental Science Department of New Mexico Tech. This procedure requires the use of split and sieved (<2mm), but not ground, samples. In the case of heavy clays, the sample was dried just short of complete drying and then chunks broken off the sample and put into the splitter. Because clays are typically homogenous already, the sample does not necessarily need to be sieved. The split sample was used in the pipette test because the peds are thoroughly soaked later on in the analysis.

Soil texture must be determined prior to weighing out samples for use in the pipette analysis. This classification, performed with a tablespoon of soil and enough water to dampen it, determines how much sample to use in the pipette analysis. Amounts of soil needed for pipette analysis is listed below:

Sand to Sandy-Loam: 40 grams
Clays and Silts: 10-15 grams
Loams: 20 grams

A soil sample was added to a pre-weighed 250 mL beaker, oven-dried overnight and then weighed ($m_{sample}+m_{beaker}$). The sample was then transferred to 250 mL Erlenmeyer flask to which is added 50 mL 10% sodium pyrophosphate and 30 mL DI/MilliPore water. A blank was also prepared with no sample, water and the dispersant in the same amounts above. The flasks were shaken for at least 4 hours, preferably overnight (~12 hours) to get a well-dispersed slurry. In the meantime, aluminum pans were weighed that will go on to hold 1) the sand fraction and 2) the fines. After 4 hours (or overnight), the contents of the flask were wet sieved with No. 200 sieve and funnel that drains into a 1200 mL Fleaker container. The contents were wet sieved by using a squeeze bottle of DI water taking care not to overfill the Fleaker past 1200 mL. What passes the sieve constitutes the caly and silt fraction. The greater than portion in the sieve was emptied into the corresponding pan for sand. The sample was dried in oven, and the dry weight ($m_{sample}+m_{pan}$) recorded. The blank was not sieved, but just added to a Fleaker and filled to volume. When all Fleakers were filled, the time was noted and shaking was initiated. The first Fleaker was shaken for 30 seconds, upon setting that Fleaker down and waiting 2 minutes to shake the next Fleaker, and so on until you have shaken all the Fleakers. Temperature of the room was noted and used to find the appropriate settling time

After waiting the appropriate settling time according to the modified Day (1965) and Jackson (1969) procedure, a pipette was used to withdraw a 25 mL aliquot of the

liquor at a depth of 10 cm. This aliquot was put into the pre-weighed ‘fines’ pan. After drying in oven, dry weight (msample+mpan) was recorded.

Percentages of sand, clay and silt are calculated according to the formulas:

$$\text{Sand } \% = \frac{(\text{Sand} + \text{Flask})\ (\text{g}) - \text{Flask}\ (\text{g})}{\text{Total Sample Wt}\ (\text{g})}$$

$$\text{Clay } \% = \frac{(\text{Clay Weight} - \text{Dispersant Weight}) * (\text{Fleaker Aliquot Volume})}{\text{Total Sample Weight}}$$

$$\text{Where Clay Weight}\ (\text{g}) = (\text{Clay} + \text{Dish}) - \text{Dish}$$

$$\text{Silt } \% = 100 - (\textit{Sand}\% + \textit{Clay}\%)$$

CHAPTER 4

RESULTS

This chapter serves to present the results of my analysis on plants, soils and water. Ideally, there would be historic environmental and geochemical baseline data from the Laguna Mining District; however, regulations were not in place until the late 1970's and so no monitoring or environmental investigations were required. Popp et al. (1988) address the lack of baseline water quality data to assess environmental changes due to uranium mining and milling in the Grants Mineral Belt. Brandvold et al. (1981) report that no records are available on water quality before mining began in the Grants Mineral Belt. Studies such as this thesis must therefore rely on comparisons between background sites upstream of mining activities and downstream sites that have been impacted by mining and milling.

4.1 Soils

A total of 46 soil samples were collected. The results of the ICP-MS analysis are shown in Appendix 2.

Soil texture was determined by pipette analysis in order to correlate clay content with uranium concentration. For the most part, the uranium values for sands are lower than that of clays and silts (Figure 10, 11 and Appendix 2). In some cases, sands have high

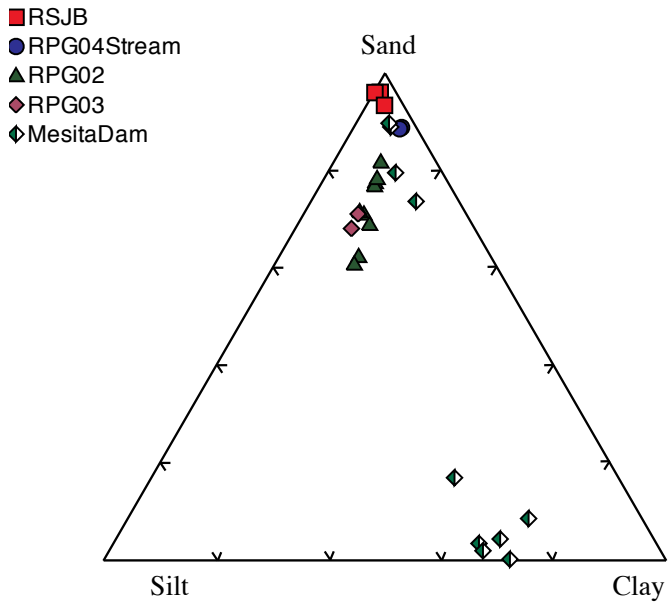


Figure 10. Ternary plot showing soil distribution from sites with U concentration below 1.355 ppm.

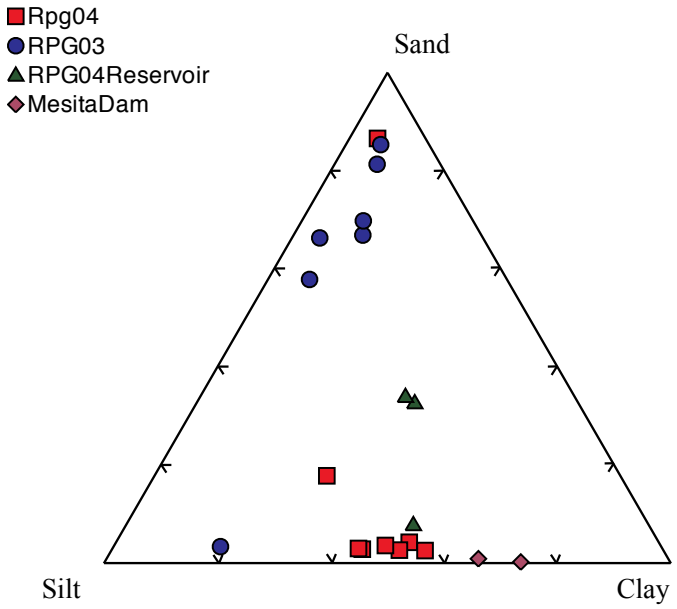


Figure 11. Ternary plot of soil samples from sites with U concentration above 1.355 ppm.

values as well as shown in Figure 11. Soil samples were taken from 12 inches deep, 6 inches and the top layer of soil. The top layer was often a sheet of sand that had been deposited.

For Figures 10 and 11, background concentration was set at 1.355 ppm because this value was the highest concentration found in soils from the two background sites upstream of Jackpile Mine: RSJB and RPG02 (Appendix 2).

4.1.1 RPG02: Background Site on the Rio Paguate

Analysis of soil at this site showed an average of 1.08 mg U/kg soil (Figure 12). This site had soil that was mostly sands, loamy sands or sandy loam and was a darker gray color that reflected its organic matter content. A higher organic matter content would be typical for a forest soil such as this one. Uranium content reached a maximum of 1.355 mg U/kg soil on the north bank at a depth of 6 inches, in sandy soil (Appendix 2). This site had the higher of the 'background' uranium concentrations with the lowest of nine samples analyzed being 0.8589 mg U/kg soil collected from the channel and was primarily sand. Another sample, also from the channel, showed slightly higher uranium contents (1.079 mg U/kg soil) and was mostly sandy soil. Clay content was higher in soils here than RSJB (Appendix 2). Similar to RSJB in soil texture, the soils were loamy sand to sandy loam (Figure 13).

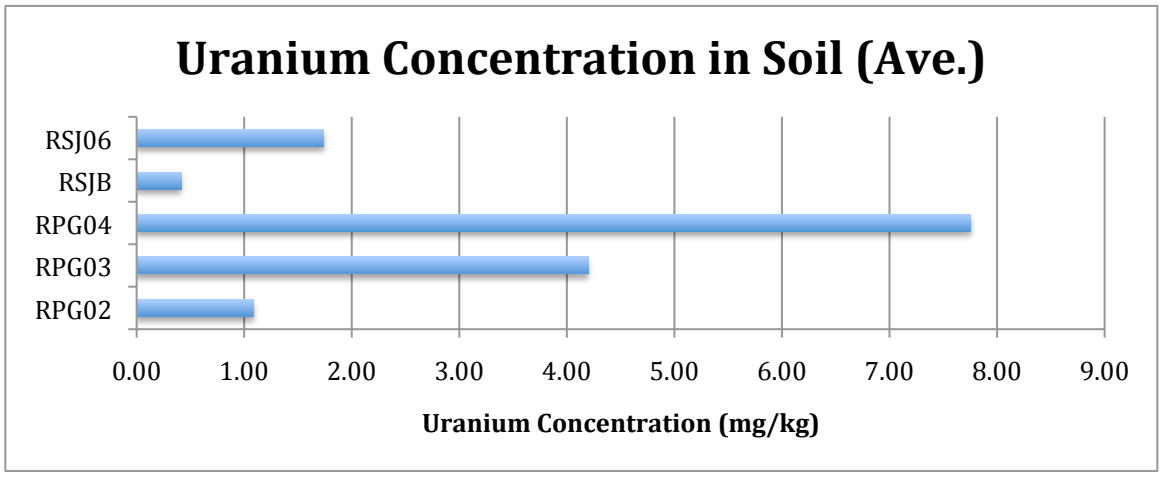


Figure 12. Comparison of the average uranium concentrations of all sampling sites.

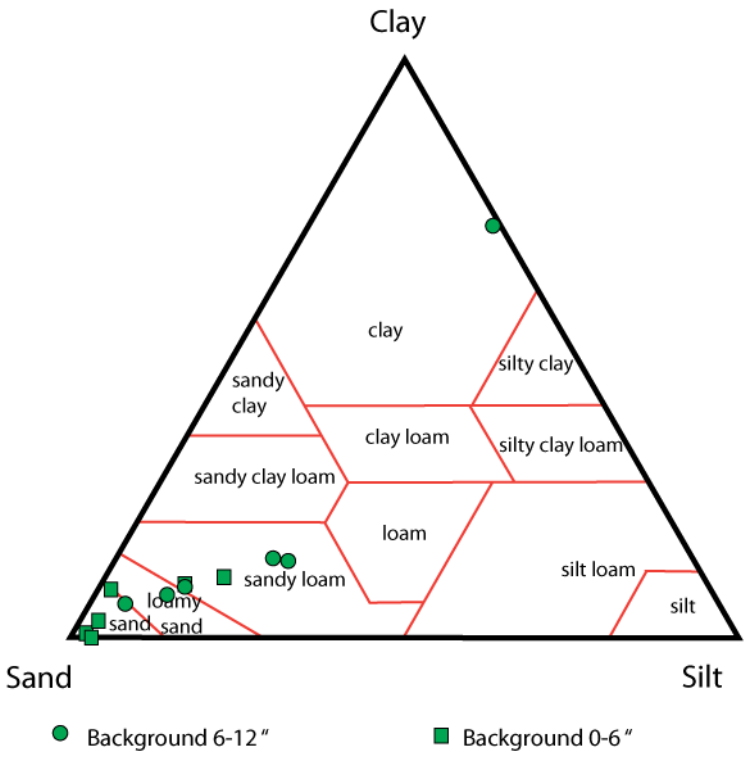


Figure 13. Background soil distribution.

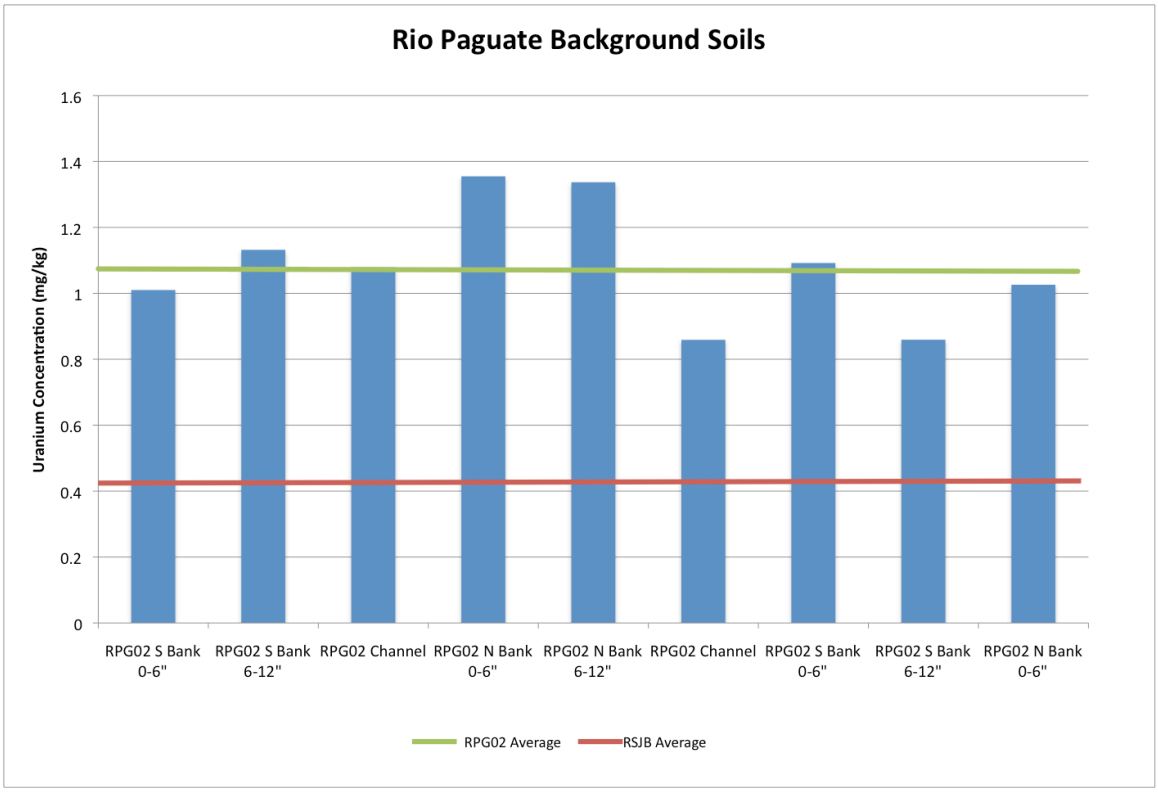


Figure 14. Uranium concentrations in soils at RPG02 with the averages shown for both background sites.

4.1.2 RSJB: Background Site on the Rio San Jose

The south bank of the Rio San Jose was sampled because the north bank was disturbed due to recent bridge construction in the area. This site had the lowest average uranium concentration of all the sites at 0.414 mg U/kg soil (Figure 12). This area was sandy, and only 3 samples were collected here. The lowest overall uranium concentration of all sites was collected at this site: a 0.3218 mg U/kg soil from the June 2011 sampling trip (Figure 14). The highest concentration was 0.5491 mg U/kg soil; it is slightly lower than the lowest soil uranium concentration from the RPG02, the Rio Paguate background site (Table 6). Soil texture is given in Appendix 2, and was shown to be more sandy than RPG02.

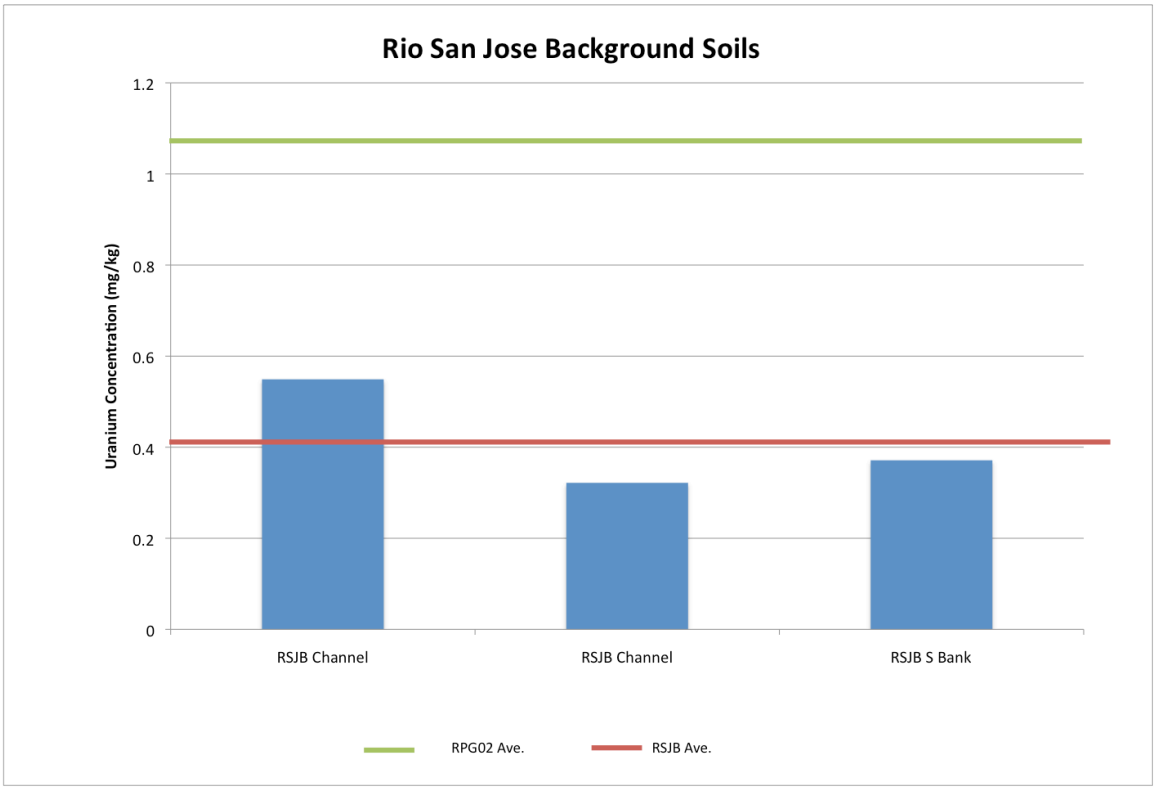


Figure 15. Uranium concentrations in soils at Rio San Jose Background with the averages shown for both background sites.

4.1.3 RPG03: The Rio Paguate Downstream of the Jackpile Mine Boundary

This site showed an average of 4.198 mg U/kg soil (Figure 12). This average is 4 times higher than background at RPG02 (upstream of the mine). All samples collected here had a uranium concentration above 1.0 ppm uranium (Appendix 2, Figure 16). The highest value was 7.243 mg U/kg soil collected September 2010 and was a sandy loam. The lowest value was 1.542 mg U/kg soil also from September 2010 and was a sand (Appendix 2). The samples collected at this site were mainly sand and silty sands and one silty clay from the channel as shown in Figure 16. Samples from the reservoir bottom, collected during times when there was no water, or little water.

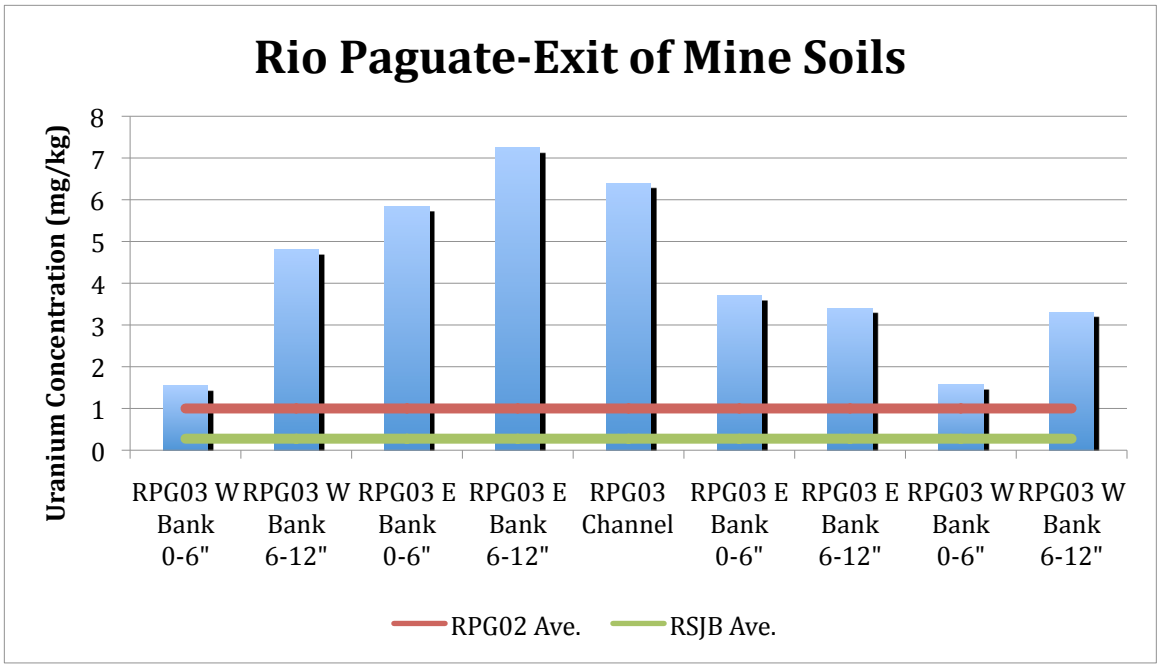


Figure 16. RPG03 soil uranium concentrations with the averages shown for both background sites.

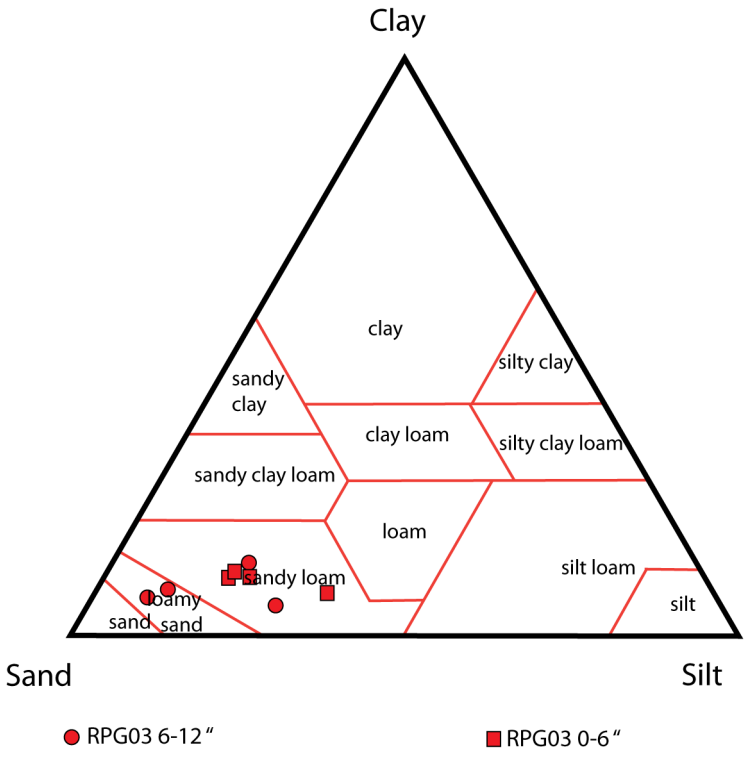


Figure 17. Soil texture at RPG03.

4.1.4 RPG04 and Surrounding Area

A total of 13 samples were collected from RPG04 and surrounding areas that include the channel entering the dam and the area closer to the dam. This site had the highest average uranium concentration at 7.754 mg U/kg soil (Figure 12). The maximum concentration was 31.44 mg U/kg soil collected in August 2009 (Figure 18). The lowest concentration was 0.5486 mg U/kg soil collected in June 2011 from the channel (Appendix 2). Samples from the Paguate Reservoir had the higher values and were silty clays (Figure 19). The channel contains silty clays and sand.

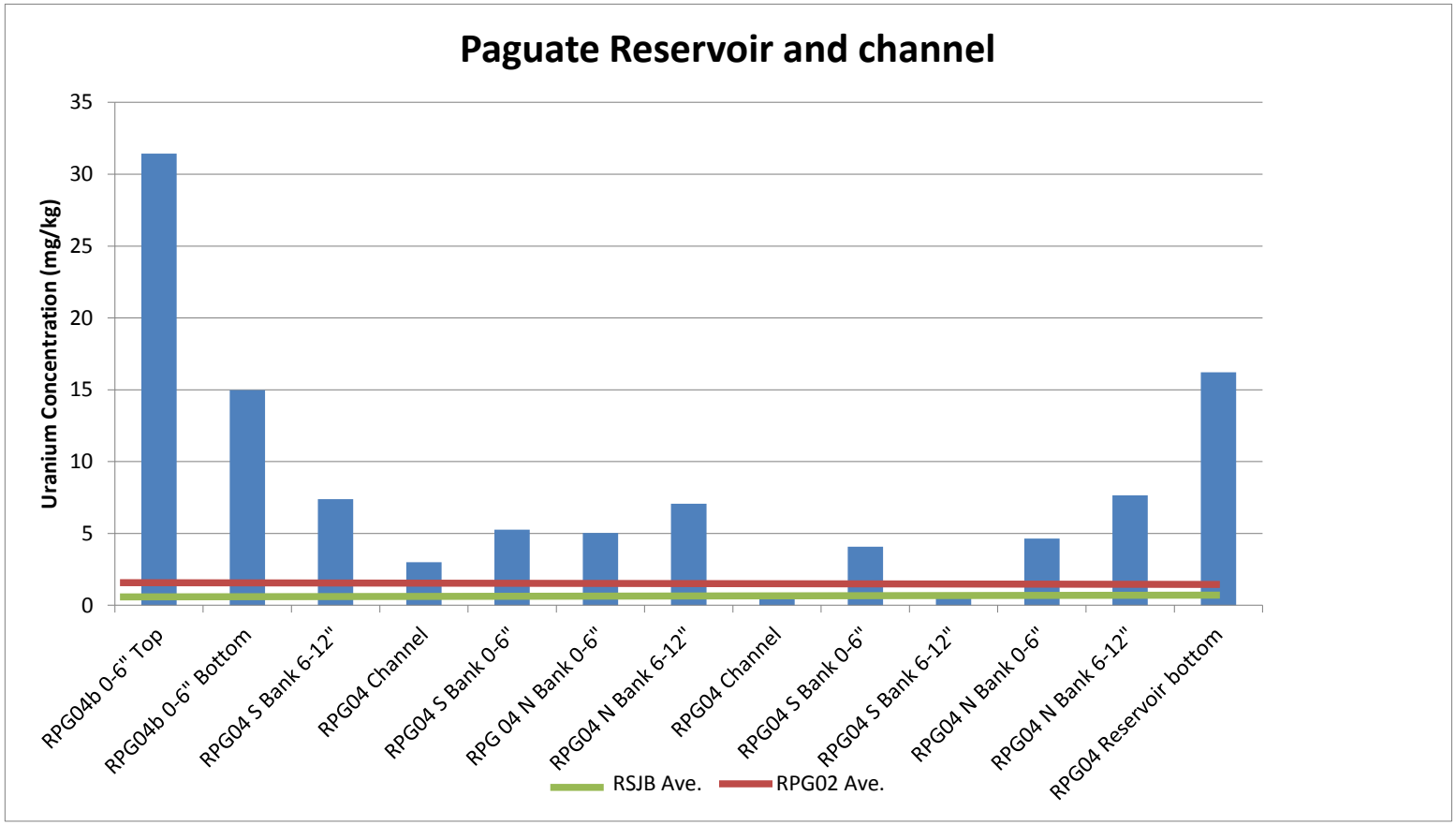


Figure 18. Uranium concentration of soil samples from RPG04 with the averages shown for both background sites.

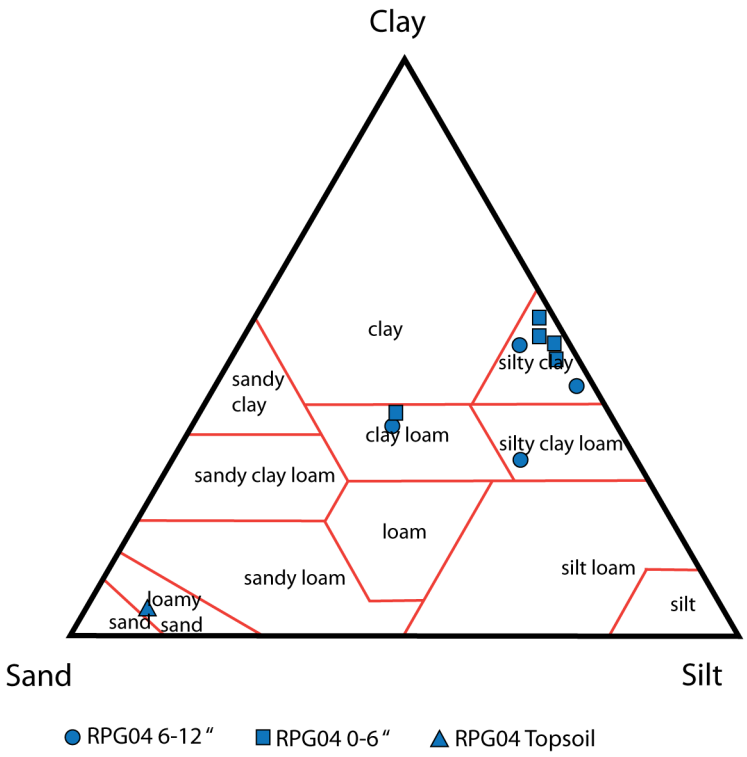


Figure 19. Soil texture at RPG04.

4.1.5 RSJ06: Rio San Jose at the Mesita Diversion

A total of 12 samples were collected from this site. This site had an average uranium concentration of 1.739 mg U/kg soil (Figure 12). The lowest value was 0.6596 mg U/kg soil collected in October 2011. The maximum value was 4.827 mg U/kg soil collected in 2009 and consisted of a dense black clay taken from the channel behind the small irrigation diversion (Figure 20). Clay content here varied between the banks and channel. The banks generally had a silty soil, while the channel held clay and sandy soil, Figure 21. Of the three sites downstream of the Jackpile Mine, RSJ06 had the lowest average uranium content in soils as well as the lowest maximum uranium content.

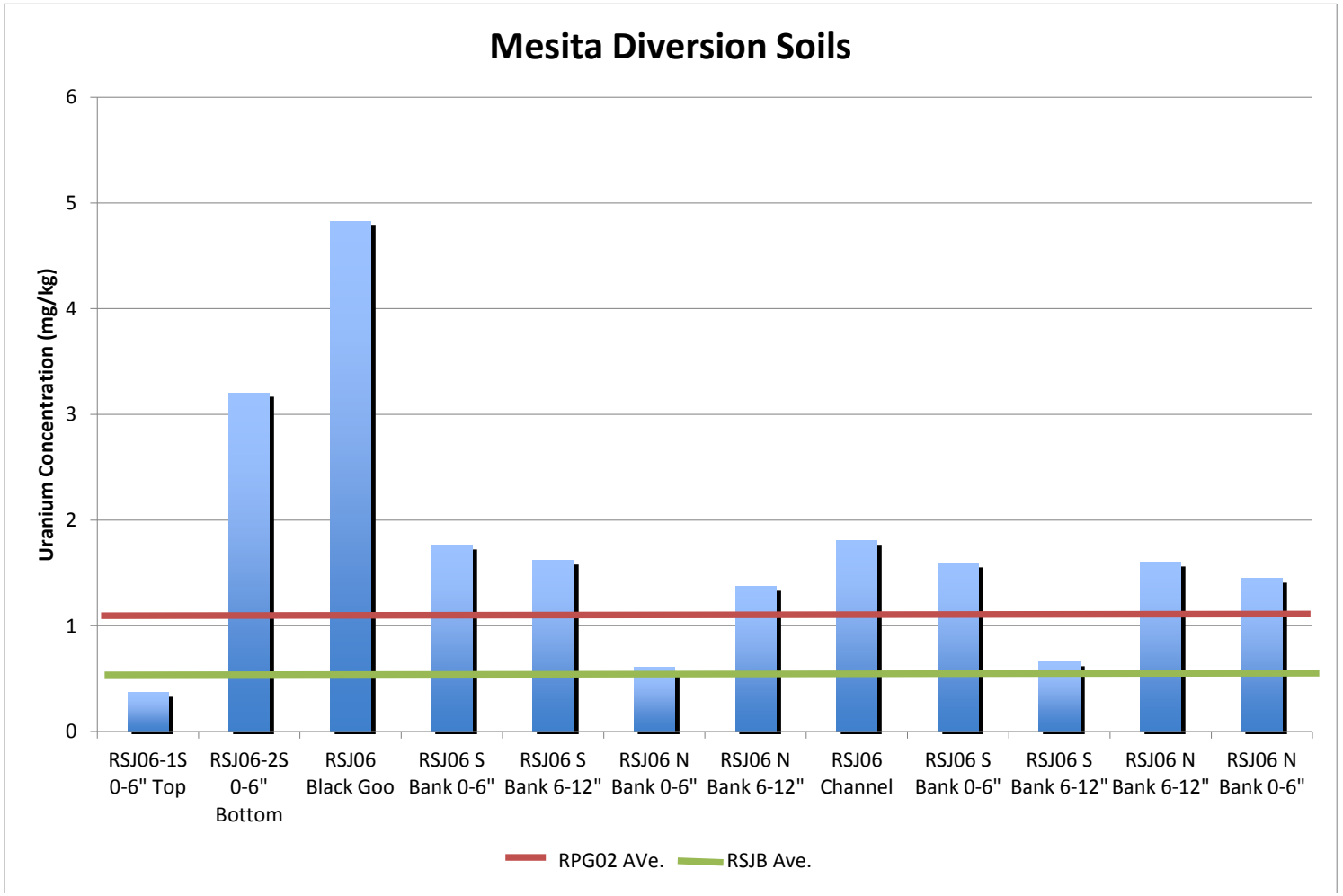


Figure 20. Uranium concentration in soils at RSJ06 with the averages shown for both background sites.

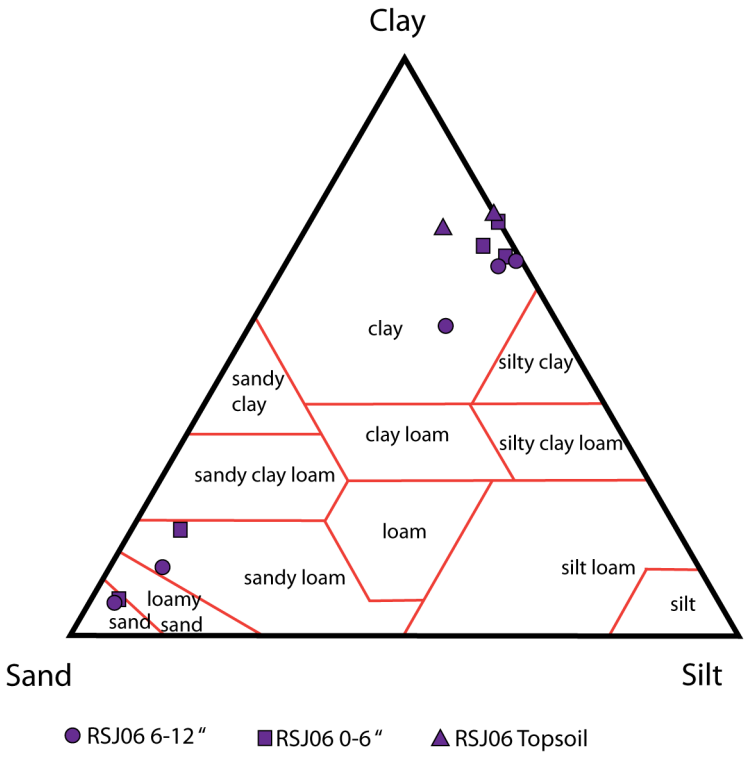


Figure 21. Soil texture at RSJ06.

4.2 Plants

A total of 97 plant samples were collected from the study area, including trees, shrubs, grasses and forbs. All plant sample collected are shown in Table 6. These plants were identified with assistance from various experts on New Mexican plants, but identification is incomplete for a few of the plants because of poor preservation of the plant sample.

Uranium analyses performed on vegetation samples are shown in Appendix 3. The sites immediately downstream from the Jackpile Mine on the Rio Paguate show the highest value for uranium in vegetation. Plants that had the highest value for uranium

were salt cedar, white clover, sedge, bulrush, cattail, milo, prickly lettuce and an unidentified*juncus*. The highest uranium value of any plant was found in an unidentified underwater grass that grew downstream of the Rio Paguate Reservoir in 2011. The range of uranium concentration is so great between plants at the same site that it is probably not useful to obtain an average concentrations based on sites. Results from sites RSJB and RPG02 yielded some plants with uranium higher than some plants from RSJ06, RPG03 and RPG04. Uranium concentration in forbs had the widest range of values, while shrubs and trees had a smaller spread. For the most part, plant samples showed a uranium concentration of 1 ppm (part per million, mg uranium per kg plant tissue) or less. Major outliers included the *juncus* mentioned above and the underwater grass that is not identified

A total of 12 vegetation samples were collected from the Rio Paguate background site, RPG02. The highest uranium concentration in a plant here was 0.33 mg uranium per kg of plant tissue found in red plantain growing near the stream collected in summer 2010 (Figure 22, Appendix 3). Another plant with a relatively high uranium concentration was the watercress also collected in 2010 with 0.31 ppm.

The Rio San Jose background site, RSJB, had a total of 22 plant samples (Appendix 3, Figure 23). These samples consisted of mostly forbs and grasses. Stands of willow, salt cedars, Russian olive and some cottonwoods were also present at this site. The highest uranium concentration was found in a sedge with 0.87 ppm. Another sedge was the next highest plant with 0.6 ppm. Both of these samples were collected in Summer 2010. Kochia is a common invasive species in New Mexico and it was collected at this

site during each sampling visit. The kochia uranium content seemed to decrease through time from 0.15 ppm in July 2010 to 0.0706 ppm in October 2011.

Fifteen plant samples were collected from the site closest to the mine, RPG03. The highest uranium content here was found in a bulrush with 3.432 ppm followed by salt cedar with a uranium concentration of 3.02 ppm (Appendix 3, Figure 24). The plant with the lowest uranium content was rabbit brush with 0.349 ppm. Cattails were collected during each visit and showed some variation ranging from 0.89 in July 2010 to 2.61 in June 2011 and 0.7115 ppm in October 2011. White clover was also collected for each sampling trip and maintained a uranium concentration of 0.7 ppm.The Paguate Reservoir site, RPG04, had a total of 16 samples collected including Russian olives, salt cedars and some aquatic plants. This site had the highest uranium concentration in a plant for this study (Appendix 3, Figure 25). An unidentified underwater grass was collected in October 2011 downstream of the spillway. This grass had a concentration of 23.62 ppm. The next highest, also from the October 2011 trip, was from a prickly lettuce growing in the same vicinity with 7.495 mg U/kg plant tissue. All the plants that were gathered on this trip showed relatively higher uranium concentrations than other times. Salt cedars were a relatively constantly high uranium plant with an average concentration of 2.84 mg U/kg plant tissue.

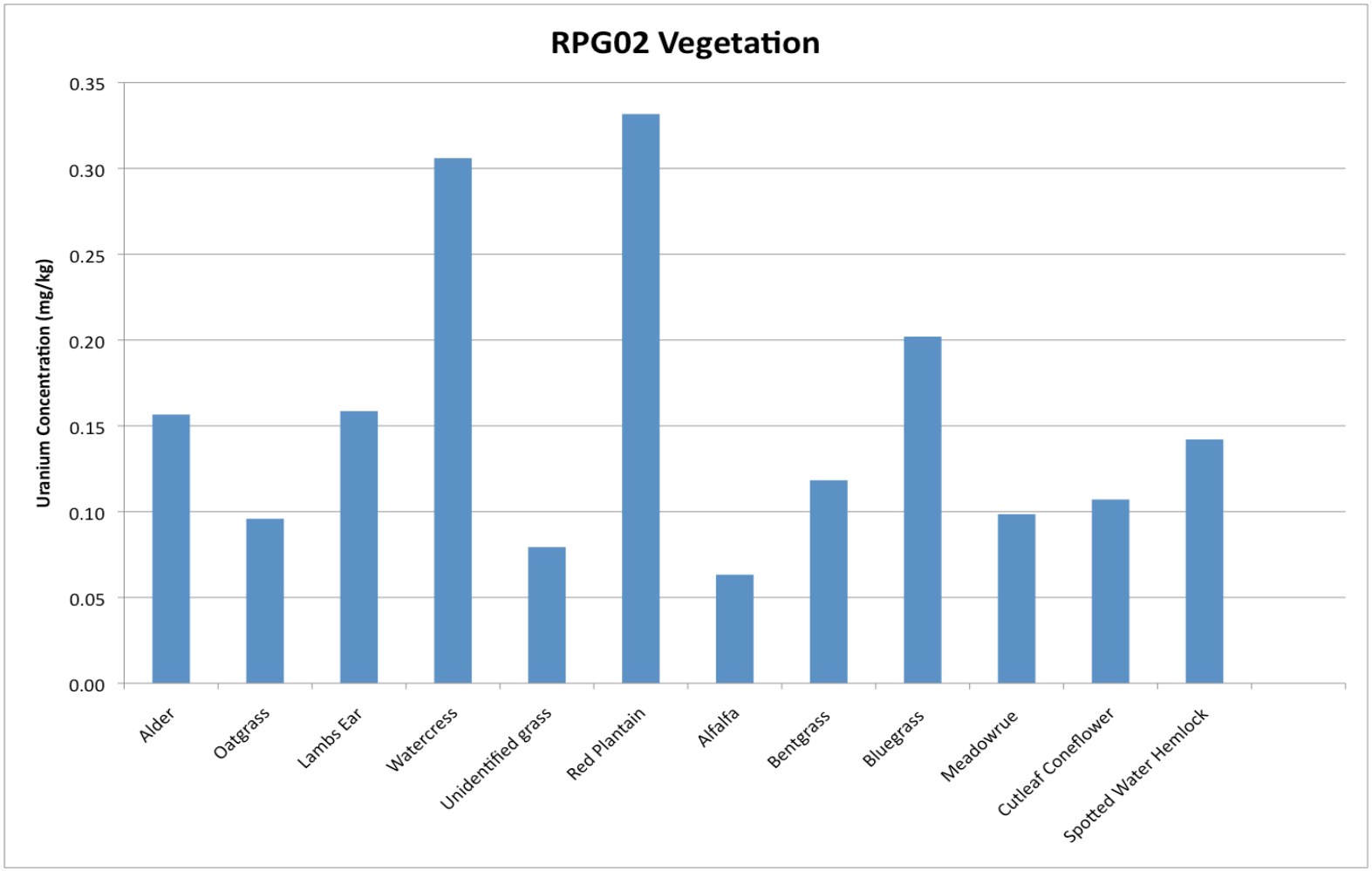


Figure 22. Uranium concentrations of plant samples from RPG02.

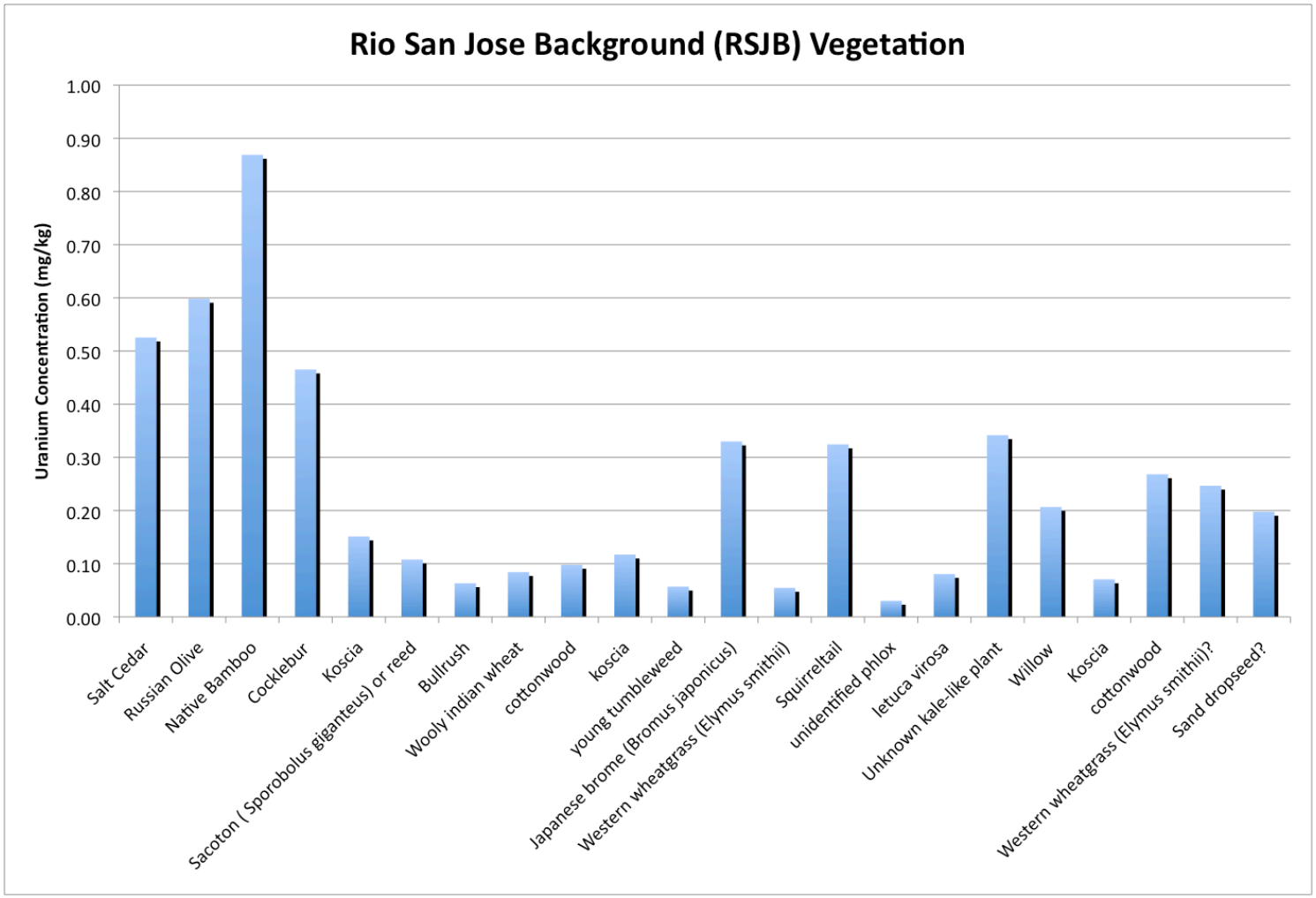


Figure 23. Uranium concentrations of plant samples at RSJB.

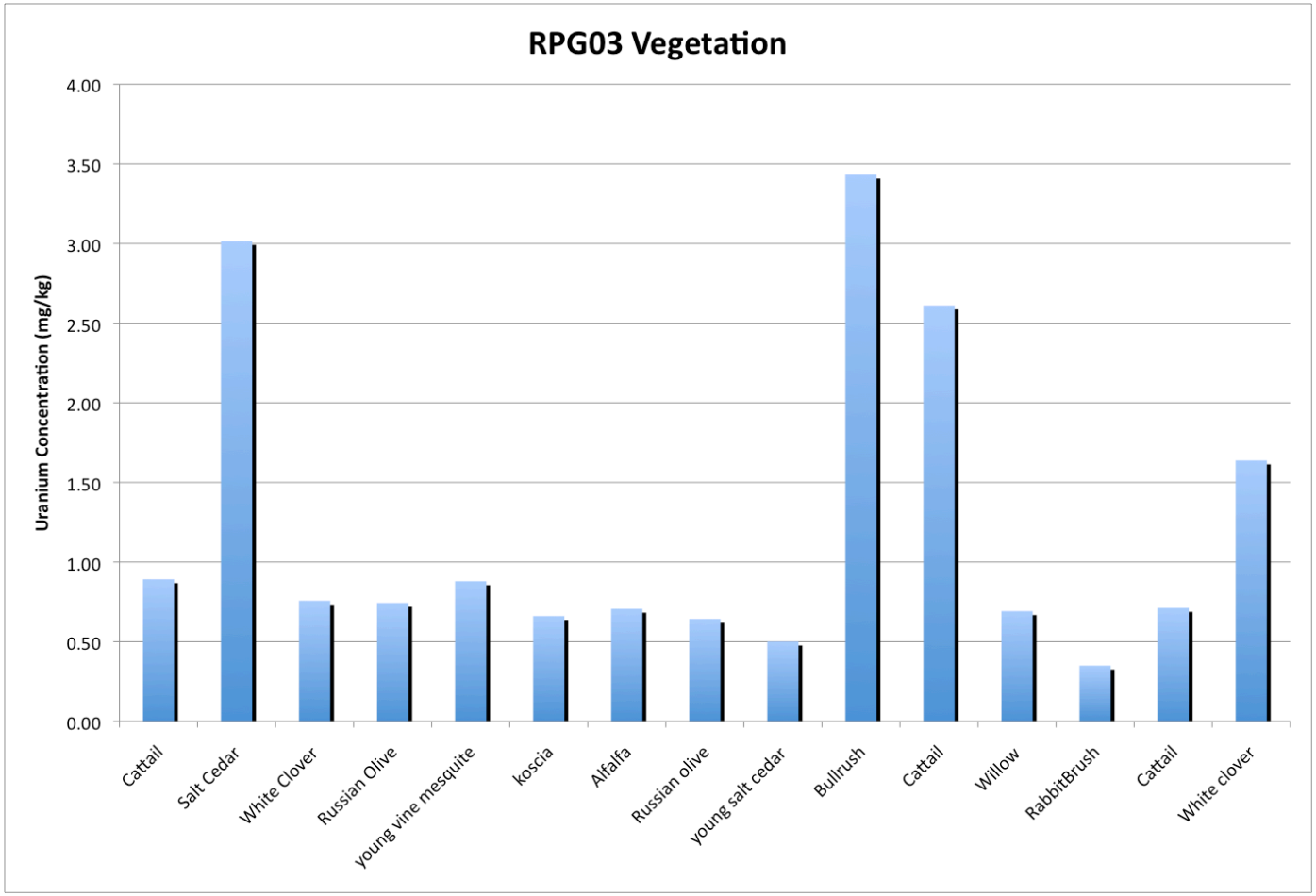


Figure 24. Uranium concentration of plant samples at RPG03.

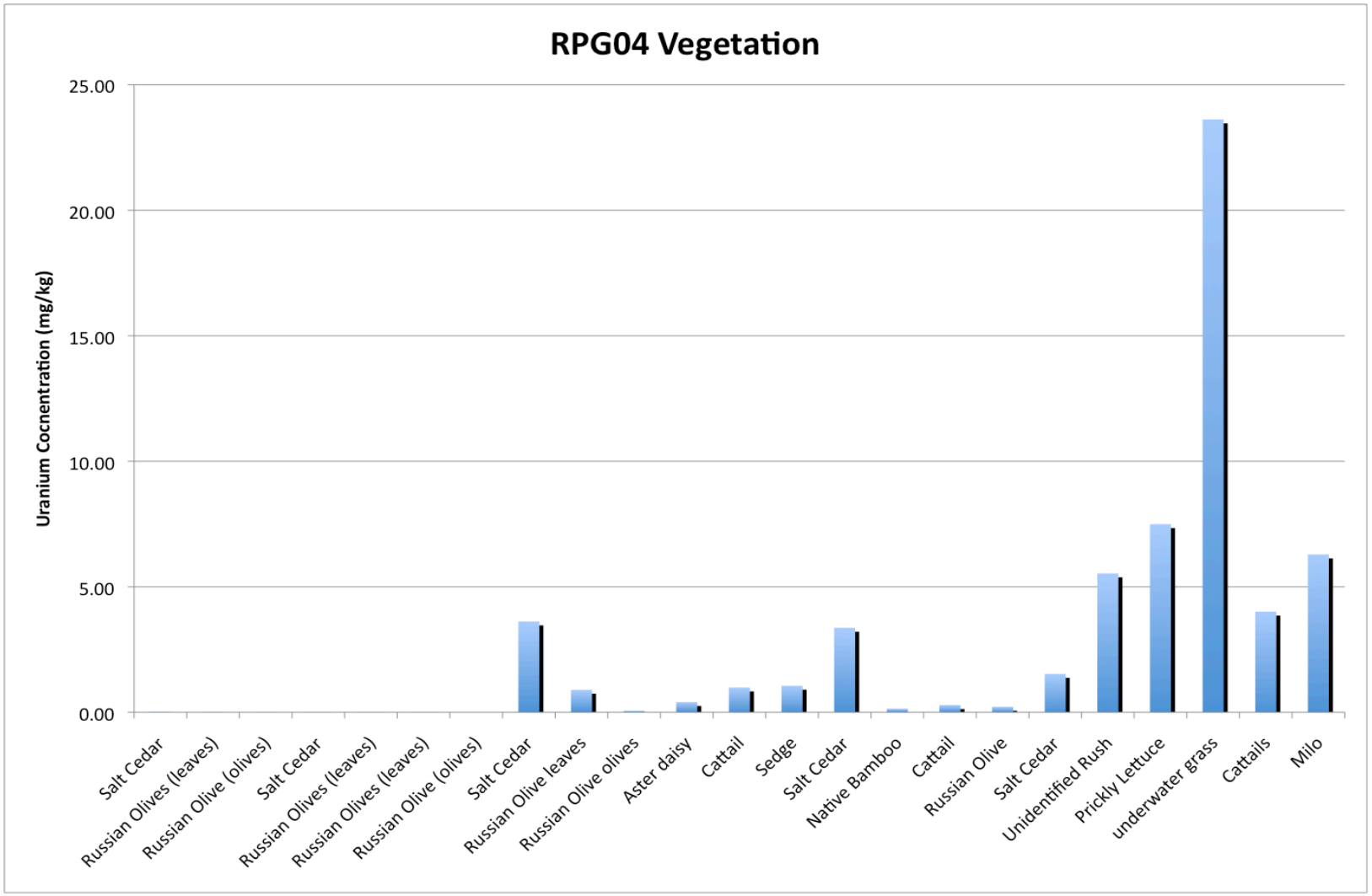


Figure 25. Uranium concentration of plant samples at RPG04.

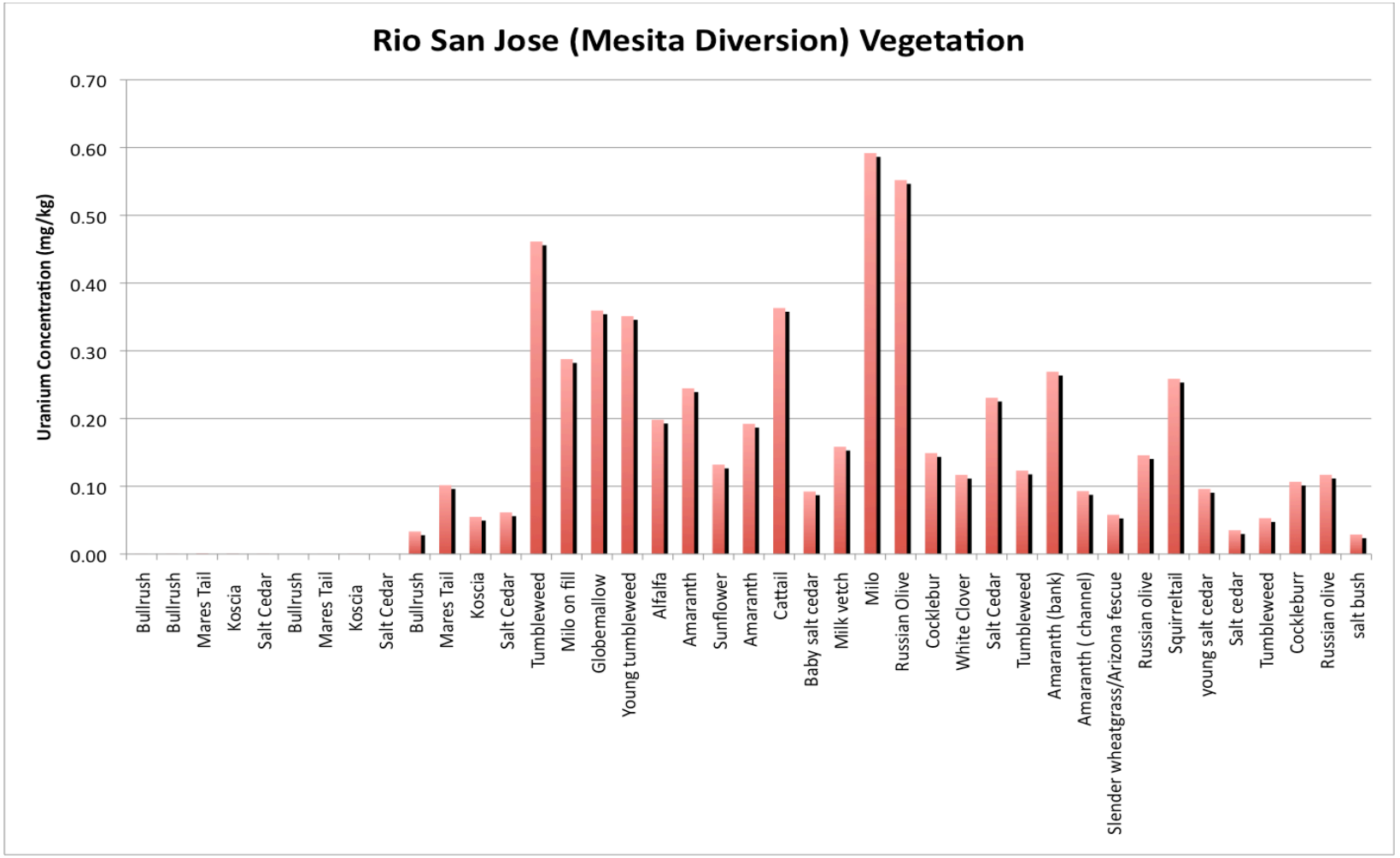


Figure 26. Uranium concentration of plants from RSJ06.

4.3 Water

Stream water samples are slightly alkaline, Appendix 4 . Other dissolved trace elements analyzed were: aluminum, antimony, beryllium, barium, boron, cadmium chromium, cobalt, copper, lead, lithium, manganese, molybdenum, nickel, selenium, silicon, silver, strontium, thallium, thorium, tin, titanium, uranium, vanadium and zinc. The United States Environmental Protection Agency (USEPA) maximum containment level (MCL) for drinking water is 30 μg/L and is the standard that would apply to these streams due to the cultural significance and traditional usage of the water.

Water data collected in this study is extremely limited. This was due to scheduling complications, and safety consideration that did not allow for sample collection to coincide with water being present at the sites. Water data from this study is presented in Table 5.

Table 5. Water uranium concentration data from this study.

	Uranium Concentration (ppm)
RPG02	
2010	<0.001
RPG03	
2010	0.46
RPG04	
2009	0.098
2010	0.021
RSJ06	
2009	<0.02
2010	0.005

CHAPTER 5

DISCUSSION

The total uranium concentrations in soils and plants of the Rio San Jose and Rio Paguate are highly variable, even between plant species. One major possibility for this variation is distance from the mine and local variations in the soil uranium concentrations. The site, RSJ06, is the farthest site downstream from the mine and has lower plant and soils U concentrations than RPG04. The main species of plant taking up uranium in the stream systems are salt cedars, cattails and in general, vegetation that grows in water. The data gathered indicates that the Rio Paguate at the exit of the mine and the Paguate Reservoir have the highest uranium build-ups. This is shown in the soils and vegetation that are above background levels. The data is not consistent, however, and salt cedars are also among the lowest in uranium concentration in other sites and the Paguate Reservoir. Variations seen in plant concentration may be caused by having different amounts of uranium in the soil at the same site. Plants were gathered based on what was available during that particular growing season and sampling trip. The same species of plant was collected from multiple sites in multiple years when possible, but were taken from the soil in an area that did not have that plant the next year. Plant samples were mainly mature, larger plants that would yield at least 3 grams of dried

material for analysis. Much effort was made to keep as close as possible to the established transect lines when collecting both soil and plants samples.
The same plants did not grow in the same spot every year however, therefore, sample collection was from a vicinity, and not from a precise spot every year.

5.1 Uranium in Plants

The total uranium concentrations in soils and plants of the Rio San Jose and Rio Paguate were highly variable, even between plant species. The background sites have lower uranium concentrations in both plants and soils than the other sites, RPG03, RPG04 and RSJ06. These three sites have varying levels of uranium in soils and plants in decreasing order. One major possibility for this variation was distance from the mine. RSJ06 is the farthest site downstream from the mine and had lower plant and soils U concentrations than RPG04. However, some of the sites that would be contaminated because they are downstream from the mine have some of the lowest values for plants and soils. The highest uranium content was found in plant samples growing in flowing water that was downstream of the Paguate Reservoir when its level was quite high behind the dam. This would imply that water was seeping through the sediments and traveling through the subsurface. Dissolved uranium could be in this water and easier for plants to uptake. Because there is only shallow soil in this area, the plants would be almost completely reliant of water from behind the dam to grow. There is no soil moisture for the vegetation to draw on. Figure 27 shows the sampling location where the high uranium content samples were collected from on October 25, 2011.

Figure 27. Sampling location at RPG04 for October 25, 2011, downstream of dam.

Salt cedar, kochia, cattail and Russian olive were among the plants that often had higher uranium concentrations. Uranium concentration analyses relied on a small number of samples and sampling was carried out mainly in the summer and fall. The main species of plant taking up uranium in the stream systems are salt cedars, cattails and in general, vegetation that grows in and near water. The data gathered suggests that the Rio Paguate at the exit of the mine (RPG03) and the Paguate Reservoir (RPG04) have the highest uranium concentration in plants due to uranium content in the soils at these sites. These sites have soils and vegetation that are above background levels. The data is not consistent, however, and salt cedars are also among the lowest in uranium concentration at other sites and the Paguate Reservoir. There was some variation of uranium uptake in plants through the years, but not enough to be significant.

5.2 Comparing Uranium in Plants by Year

Uranium concentration also varies greatly annually in the same plant species from the same sample sites. Comparing the data between 2010 and 2011 shows large variations for some plants (Figures 28 through 35). The reason for variation of uranium uptake in plants through the years most likely stems from small differences in where the plant is growing and variations in the soil chemistry itself. This may have something to do with the amount of precipitation pushing uranium-laden sediments and colloids downstream of the mine or stirring up buried sediments at the Paguate Reservoir.

Only a few plants were found to be common to multiple sites: salt cedar, cattail, Russian olive, kochia and white clover. The plots demonstrate the variability for each individual plant to take up uranium. This would imply that while a species can absorb

more uranium than another species, it is not safe to say that the species will always pick up appreciable amounts of uranium.

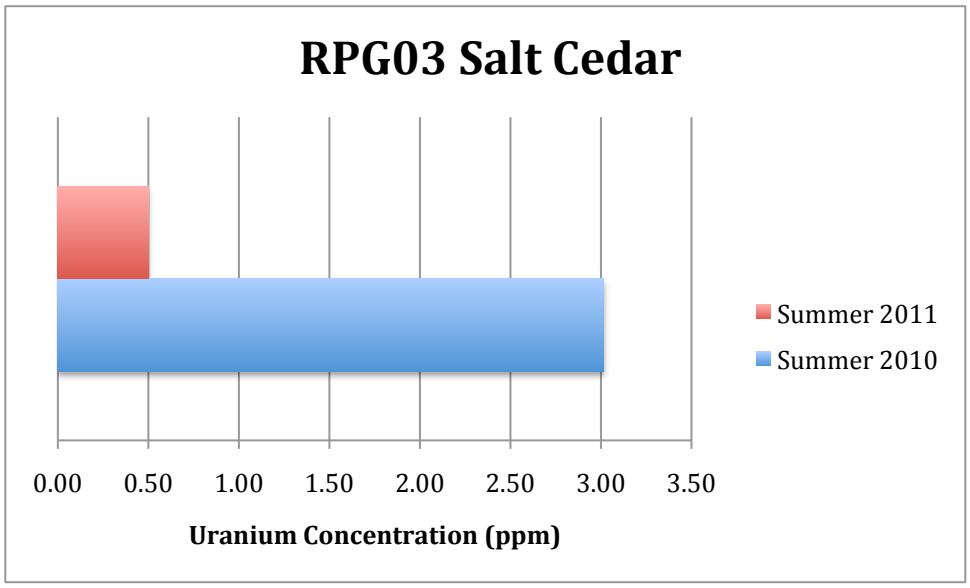


Figure 28. Uranium concentration in salt cedars from RPG03.

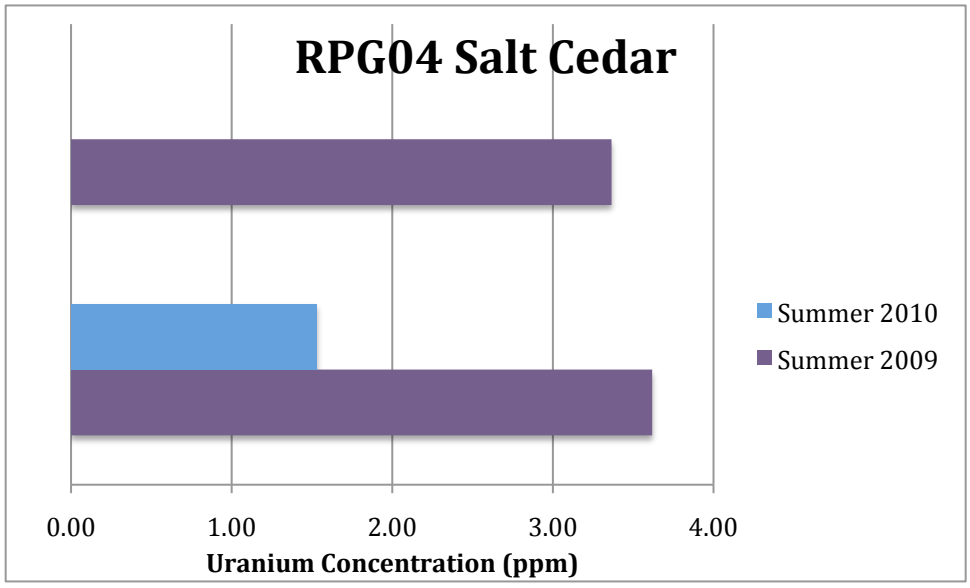


Figure 29. Uranium concentration in salt cedars from RPG04.

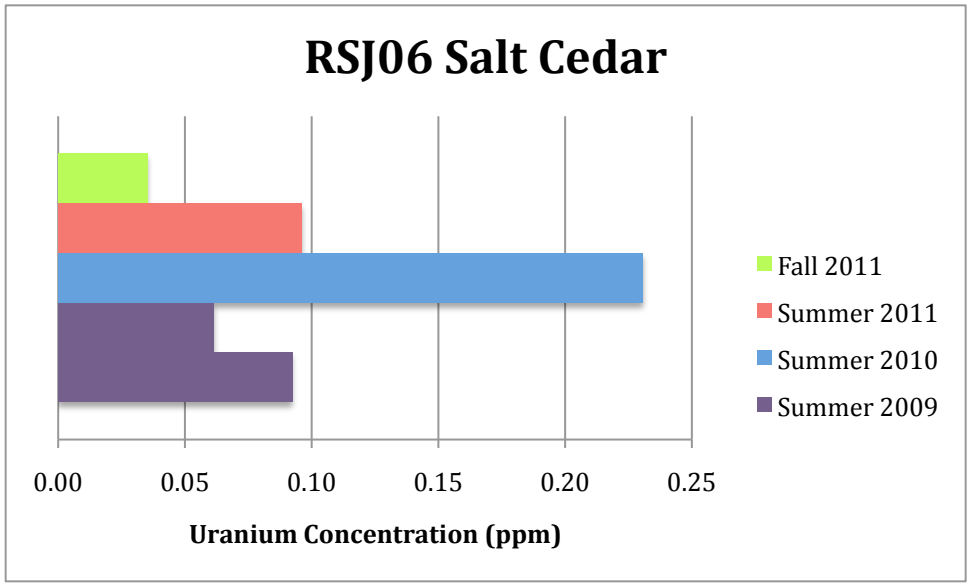


Figure 30. Uranium concentration in salt cedars from RSJ06.

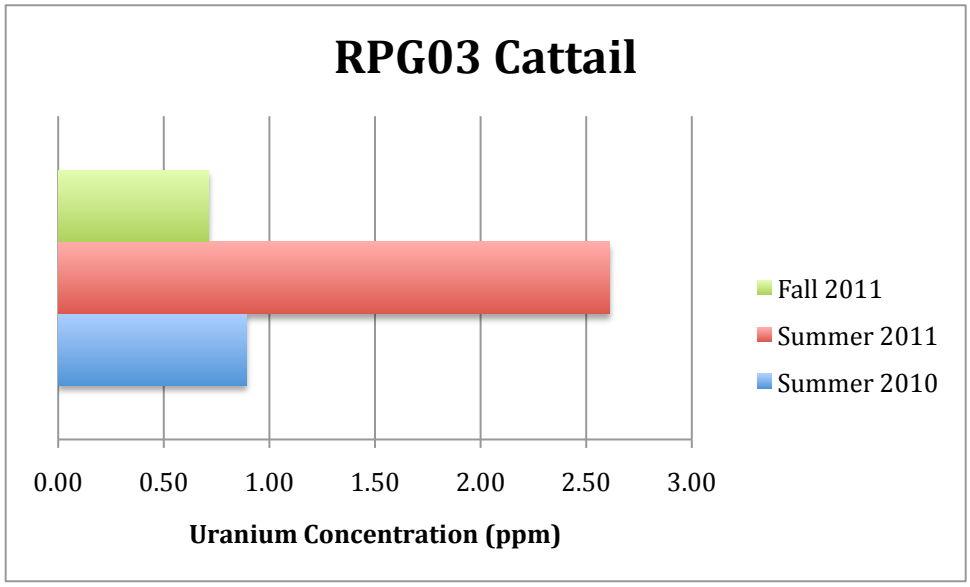


Figure 31. Uranium concentration in cattails from RPG03.

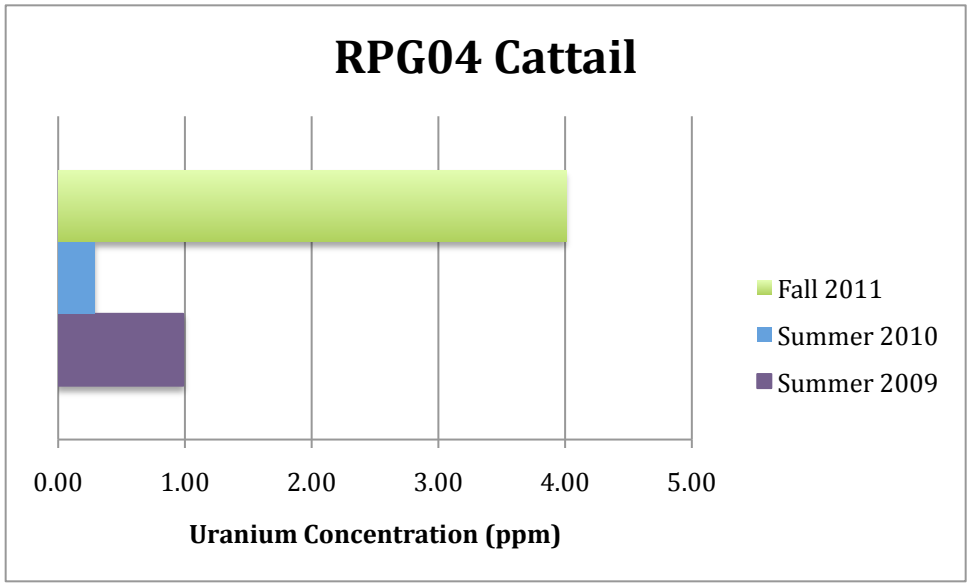


Figure 32. Uranium concentration in cattails from RPG04.

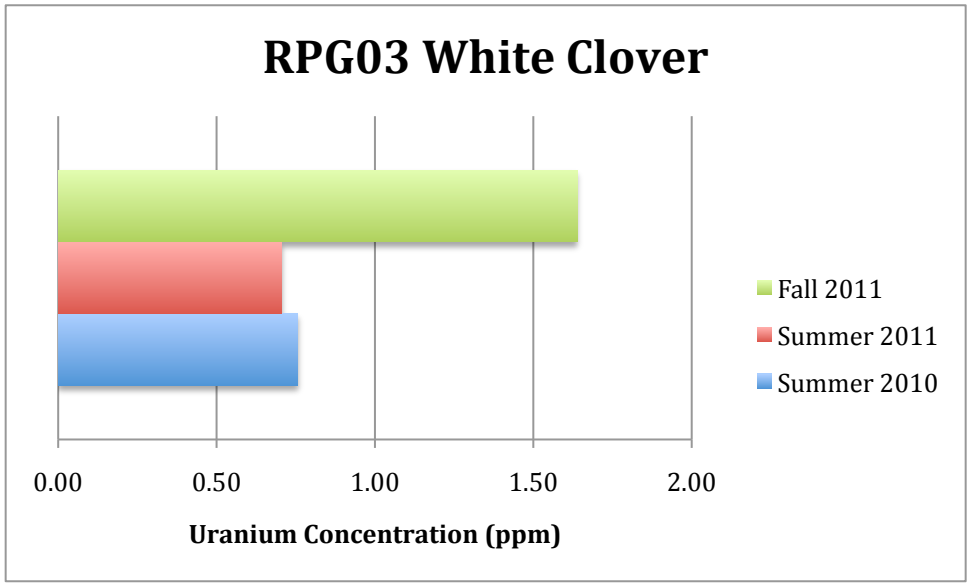


Figure 33. Uranium concentration in white clover from RPG03.

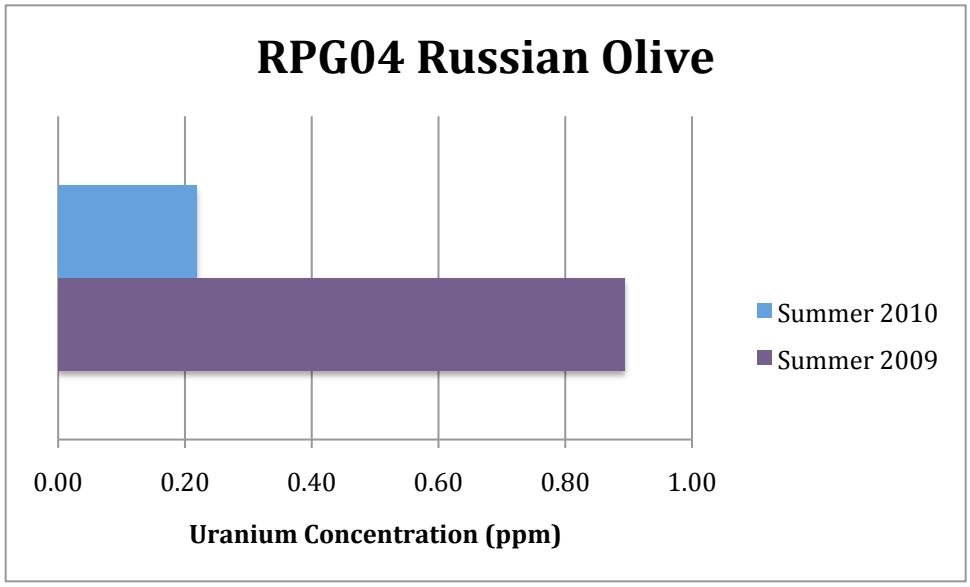


Figure 34. Uranium concentration in Russian olive from RPG04.

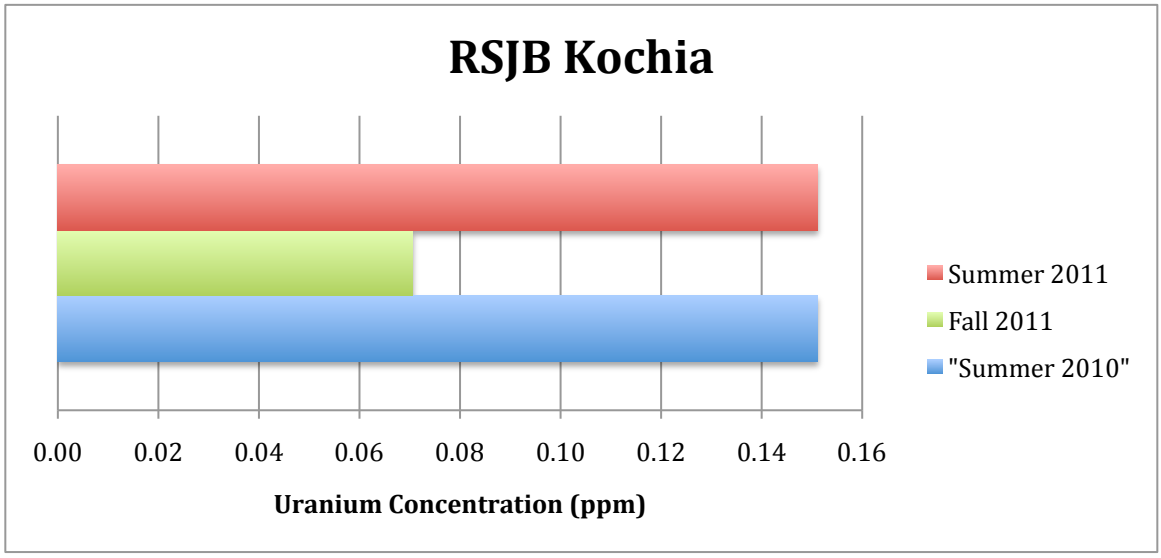


Figure 35. Uranium concentration in kochia from RSJB.

Records from NOAA taken at the Grants-Milan Airport (30 miles west of Laguna) show that the of the years 2009, 2010 and 2011, 2010 was the wettest with 10.0 inches, and 2011 was the driest with 7.57 inches (Figure 36).

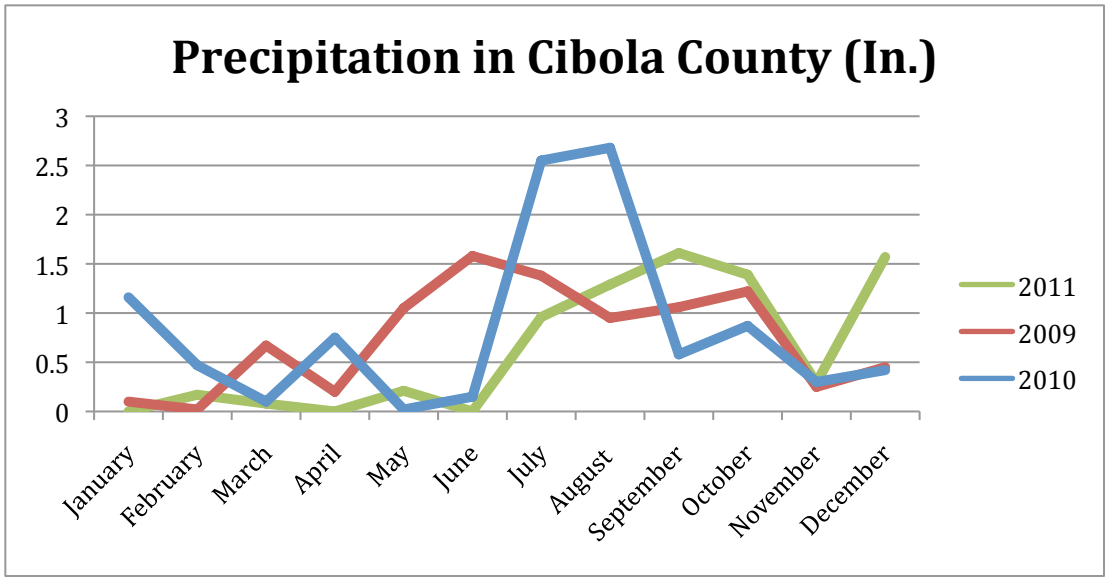


Figure 36. Precipitation totals by month for the Grants-Milan, NM, area for 2009-2011.

Figure 36 demonstrates that summer rainfall is the main form of moisture in the area, however in 2011 December had the highest precipitation. Soil moisture is related to uranium mobility and depends on the amount of time soil stays wet. The longer a soil is moist before drying out can lead to greater uranium uptake by plants. Histograms of the plant for each year, and for the soil samples for 2010 and 2011 because there was not sufficient soil data for 2009. The plant sample histogram (which was normalized to make the years comparable) shows that 2010 had more plant samples with uranium higher than 0.25 ppm U (Figure 37). This may imply that the higher precipitation level from mid-June until mid-September 2010 allowed plants to take up more uranium. Samples in 2011 were collected twice, once in July and again in September. This year also had the highest uranium in plants that were collected in October which was at the tail end of the wet period for that year. These samples collected in October contained the highest uranium content for the study. These plants were collected in pools of trickling water near Paguate Dam in cracks in the sandstone.

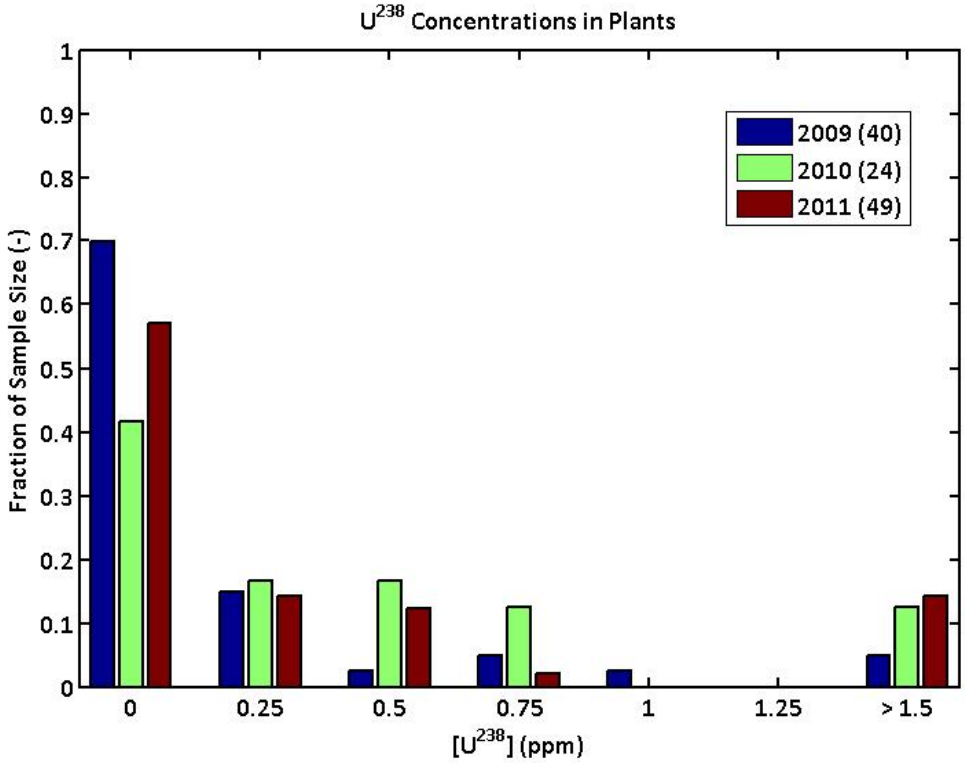


Figure 37. Normalized plant uranium content data by year with amount of samples in parentheses.

This effect of higher moisture on plant uptake of uranium may be demonstrated in this study as the higher uranium content is associated with periods of high precipitation and areas with running water present.

The histogram for the soil uranium content is given in Figure 38 and seems to demonstrate that 2010 had more samples with uranium between 2 and 6 ppm than in 2011. Soils can have particles that have uranium sorbed on to them, those particles can be transported by water to be settled out in low energy environments such as behind dams.

Soil samples for 2011 were taken in June of that year which had lower precipitation than in September of 2010 when those soil samples were collected. If uranium content in soils is affected my moisture as it is in plants, than higher uranium content in soils should coincide with higher precipitation. June 2011 had little

precipitation but had one soil sample with a very high uranium content of 16.21 ppm from the Paguate Reservoir's silty bottom. This particular sample site was accessible since there was no water there. This sample could have been comprised of several old silt deposits that did not necessarily reflect the soil uranium content for only 2011. If we discount this one sample as an outlier, 2010 ends up having the higher uranium content in samples, although slightly. It seems that the higher precipitation in 2010 increased soil moisture which may have allowed more uranium to be mobilized and taken up by plants.

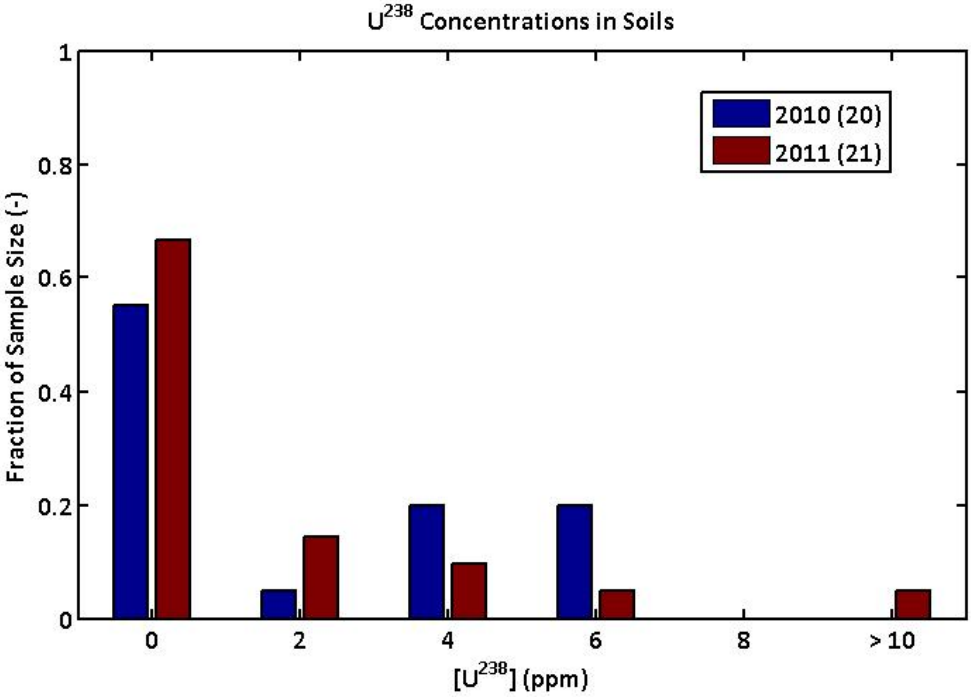


Figure 38. Normalized soil data by year with amount of samples in parentheses.

5.3 Uranium in Plants Versus Soils

Figures 39 through 43 show soil uranium concentrations plotted against the plant uranium concentrations. These figures show that the two background sites have lower soil and plant uranium concentrations. For the sites RPG03, RPG04, and RSJ06, the soils

and plant uranium concentrations are higher (Figures 43, 44, 45). These plots were made by matching the soil samples (taken from the top 6 inches of the soil) to the plant samples that were taken from the same bank, or at RSJB (Figure 40), from the channel area.

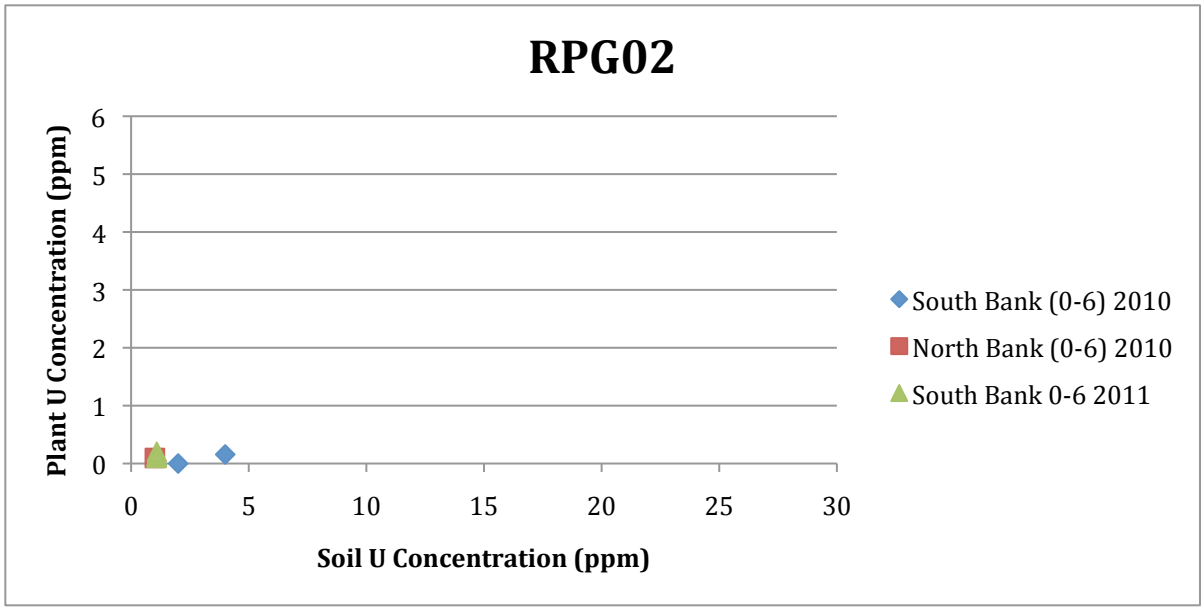


Figure 39. Comparison of uranium content in plants versus soils at RPG02.

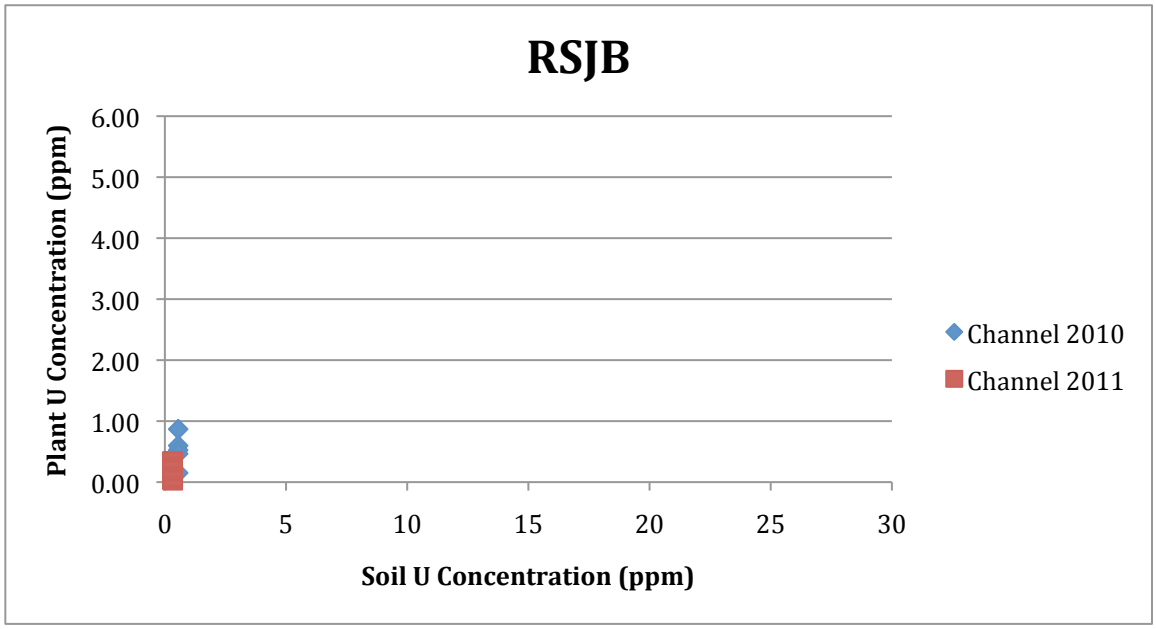


Figure 40. Comparison of uranium content in plants versus soils at RSJB.

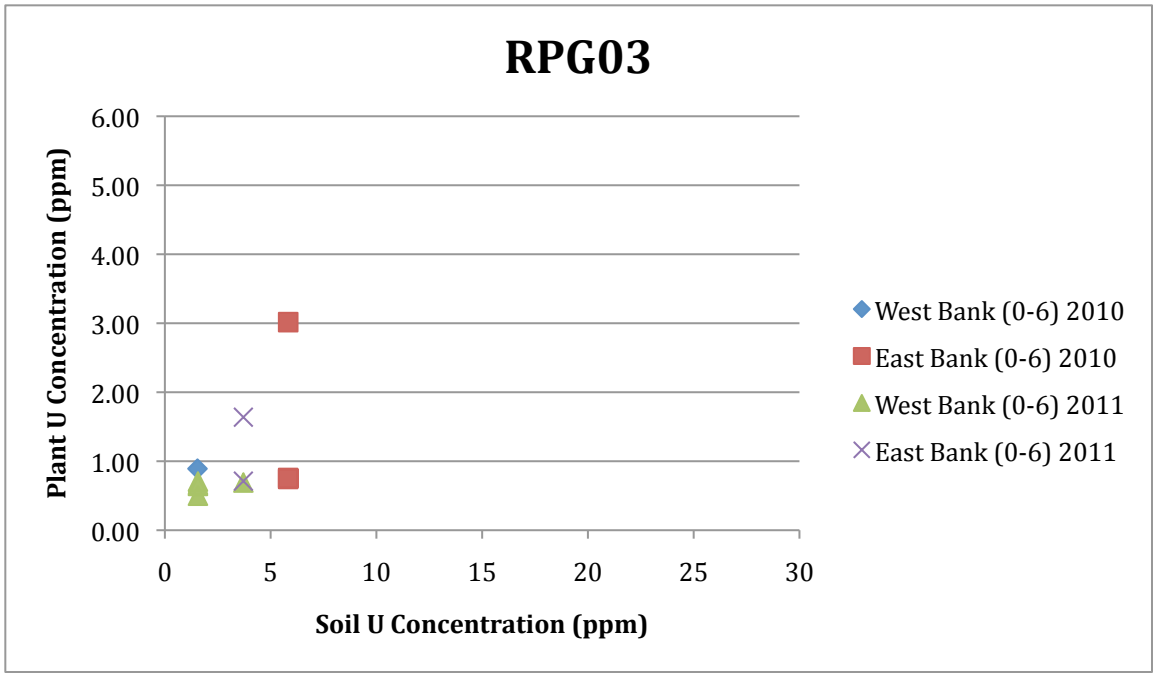


Figure 41. Comparison of uranium content in plants versus soils at RPG03.

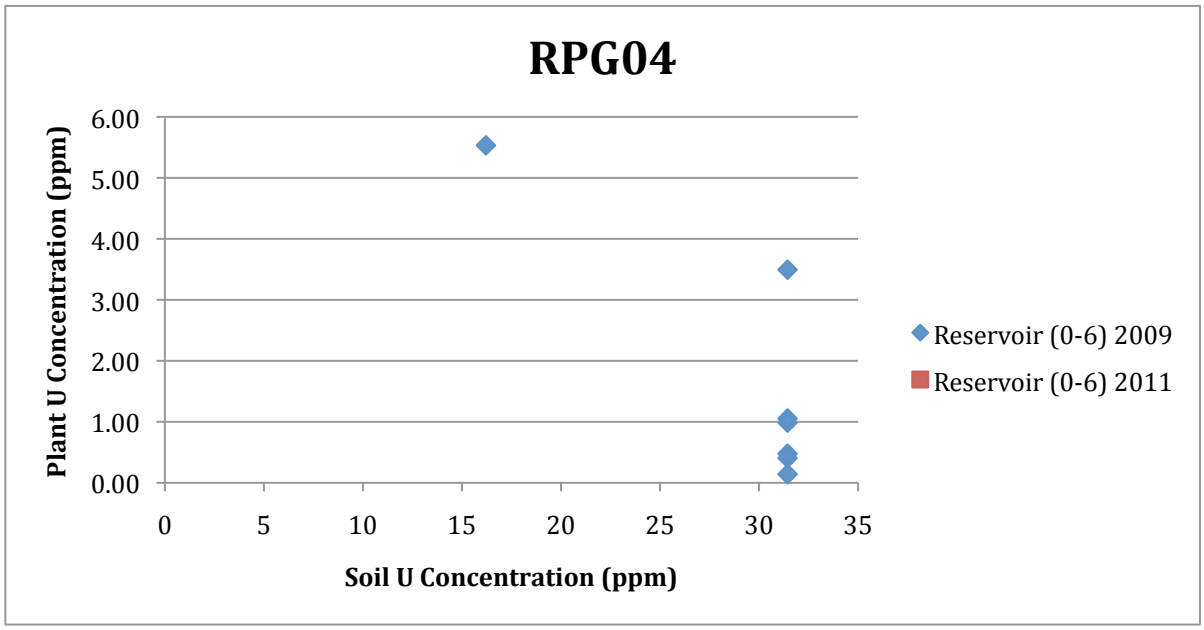


Figure 42. Comparison of uranium content in plants versus soils at RPG04.

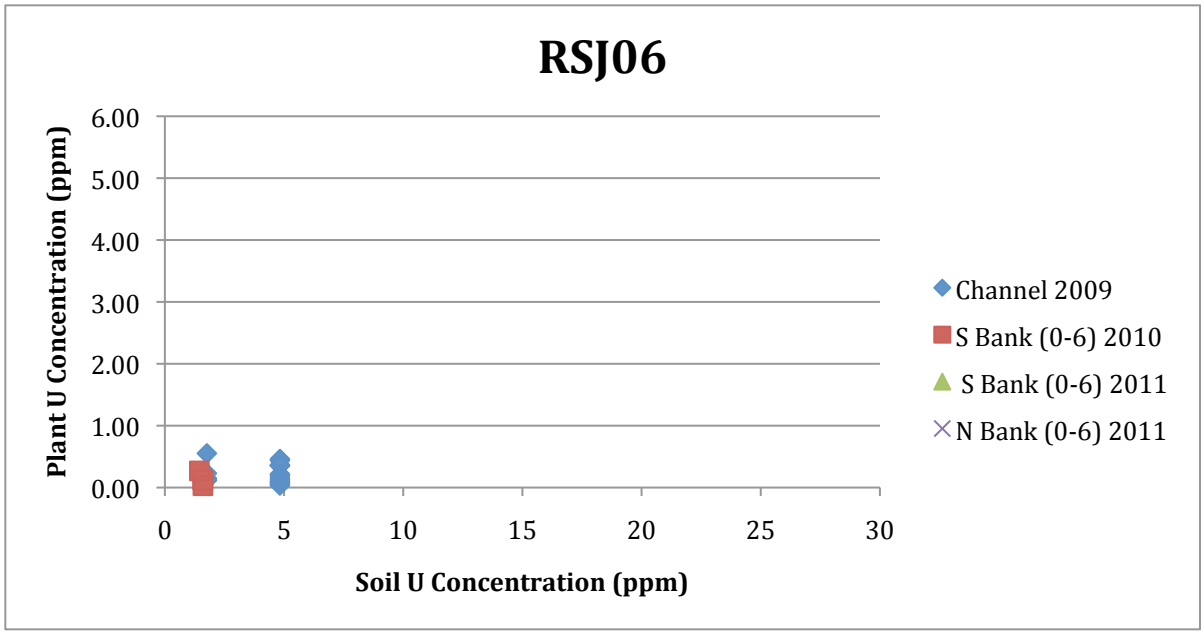


Figure 43. Comparison of uranium content in plants versus soils at RSJ06.

Figure 44 is a plot showing all the data points to provide a side-by-side comparison of all sites including the backgrounds. The values for the background are in the lower left-hand corner demonstrating the low uranium content of both plants and soils at sites upstream of Jackpile Mine.

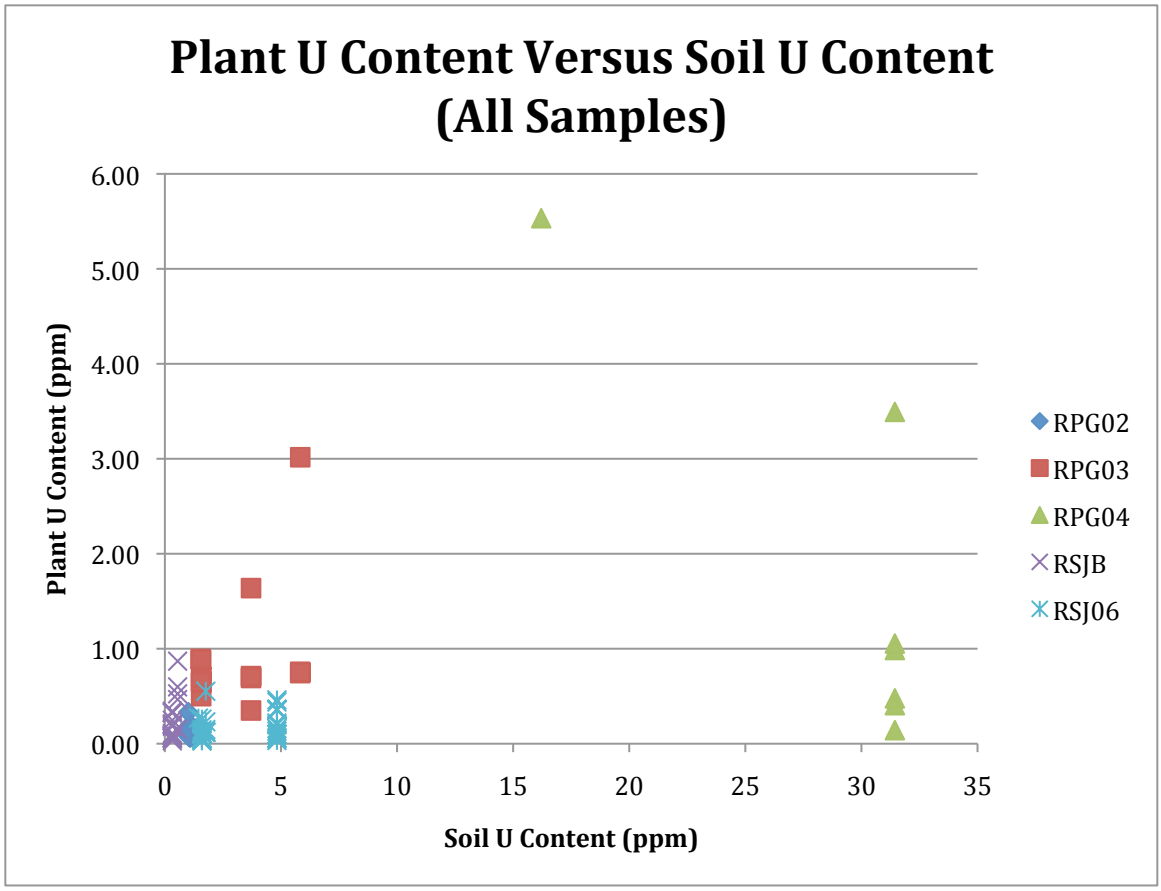


Figure 44. Comparison of all data points for plant U content versus soil U content.

A soil sample was not taken for every for every plant from the soil in which the plant was directly growing. However, some of the sites that would be contaminated because they are downstream from the mine have some of the lowest values for plants and soils. Salt cedar, kochia, cattail and some unidentified plants growing in slow-flowing or standing water were the types of vegetation that had the highest uranium concentration. To find some correlation between soil uranium content and uranium content in plants, the plot should show that the higher the concentration in the soil often leads to a slightly higher uranium concentration in plants, at least with this limited data set. RPG03 (Figure 41) and RSJ06 (Figure 43) follow this trend, but RPG04 (Figure 42)

does not. The RPG04 site was not just one single transect in a small area. Plants were gathered where available, and the location used for the soil samples at the Paguate Reservoir did not have sufficient vegetation to collect a sample from. The soils at RPG04 may not show a strong correlation between uranium being taken up by plants from the soil simply because the plants were not always collected from the same place the soils were. At RPG04, one part of the site was utilized for soil samples because a well-formed channel was present for the transect. This channel had little vegetation growing compared to the area closer to the dam, therefore there were two areas used in this sample site. At times, soil samples were collected from the area closer to the dam, and this data is labeled "RPG04 Reservoir" in Appendix 2.

Another interesting piece of information from these plots is the background sites do show relatively low soil and plant concentration. The background site on the Rio San Jose (RSJB) is slightly higher than the Rio Paguate background site (RPG02). RSJB is characterized by sandy soil and was downstream of other uranium mining and milling activities during the uranium boom.

5.4 Plant : Soil Ratio

In order to compare different plant species' uptake of uranium, Figures 45 through 49 were plotted by taking the ratio of plant uranium content over soil uranium content. The resulting ratios show that the RSJB had the closest match between plant uranium contents and the soils they were growing in. The site had disturbed soils that had recently been reworked. The area is also very sandy, and the plants growing there were in the channel which was quite sandy. This site never yielded any water samples since it

only runs during the winter and did not coincide with any of the sampling trips. During the summer, the water is used irrigation upstream. It is still unclear why the soils and plants here would have relatively higher uranium uptakes.

Uranium uptake varies greatly annually in the same plants from the same locations. Plants that live in the water have a greater potential source of dissolved uranium to absorb since they are in standing water. Terrestrial plants have only pore water from which to obtain nutrients and trace elements such as uranium.

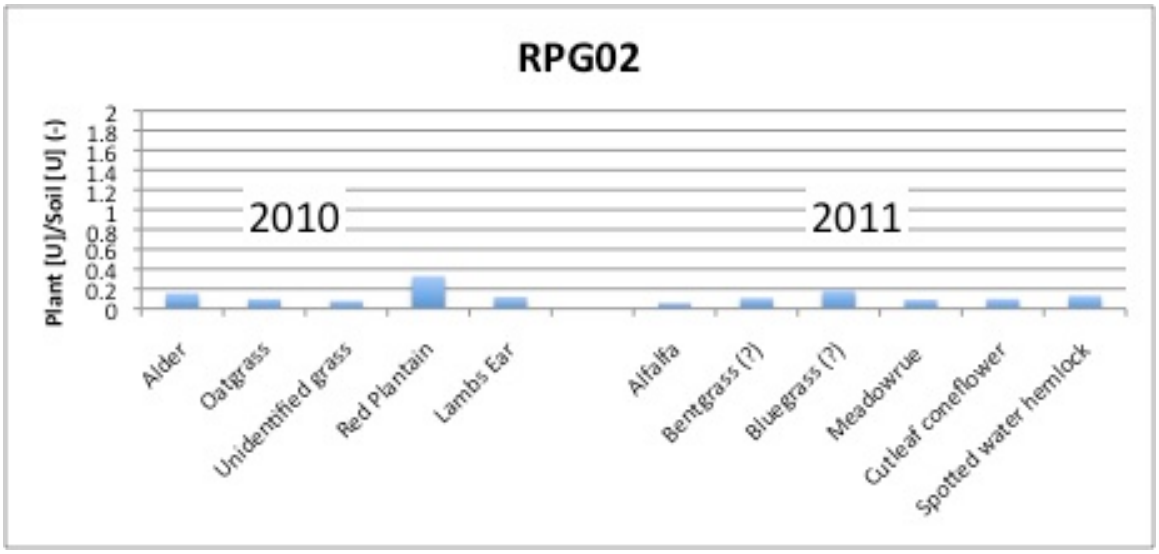


Figure 45. Ratios of plant U to soil U by plant at RPG02 [ppm/ppm].

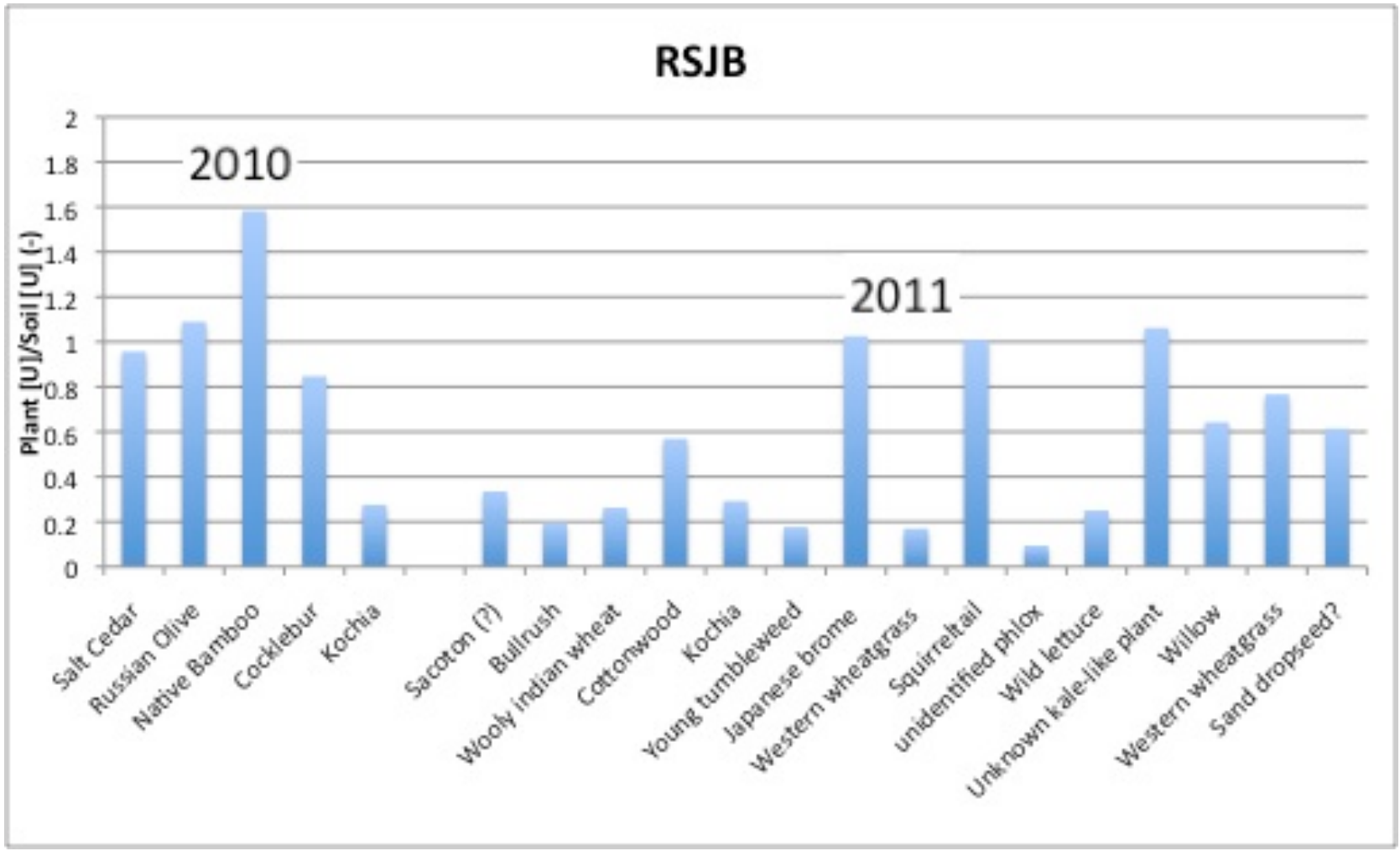


Figure 46. Ratios of plant U to soil U by plant at RSJB [ppm/ppm].

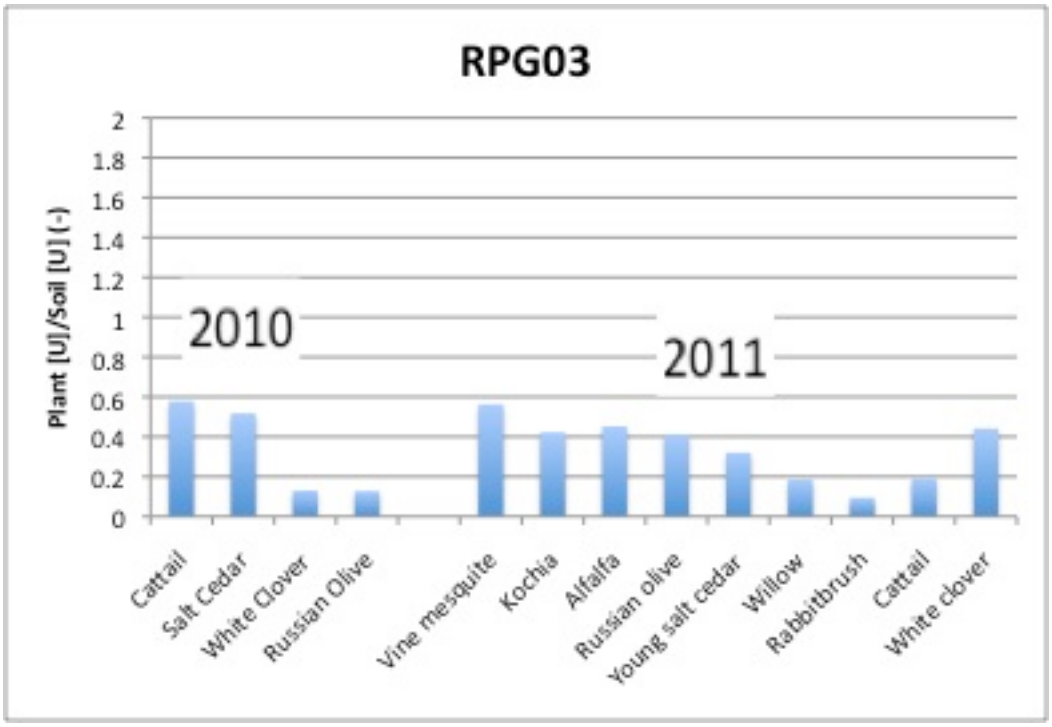


Figure 47. Ratios of plant U to soil U by plant at RPG03 [ppm/ppm].

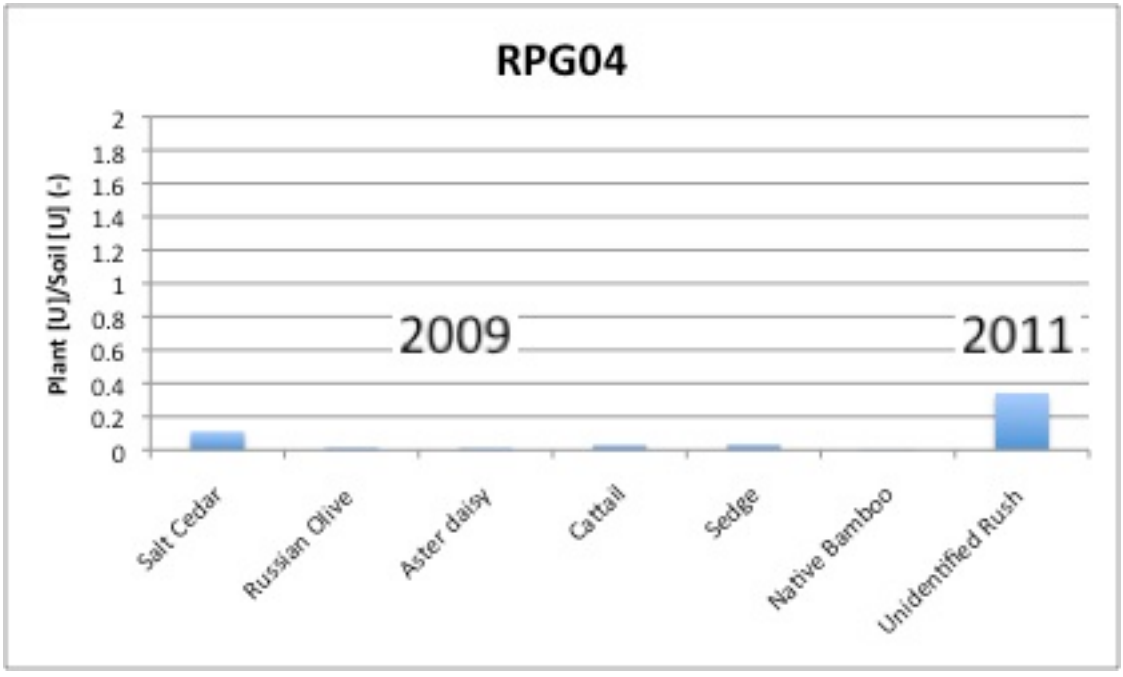


Figure 48. Ratios of plant U to soil U by plant at RPG04 [ppm/ppm].

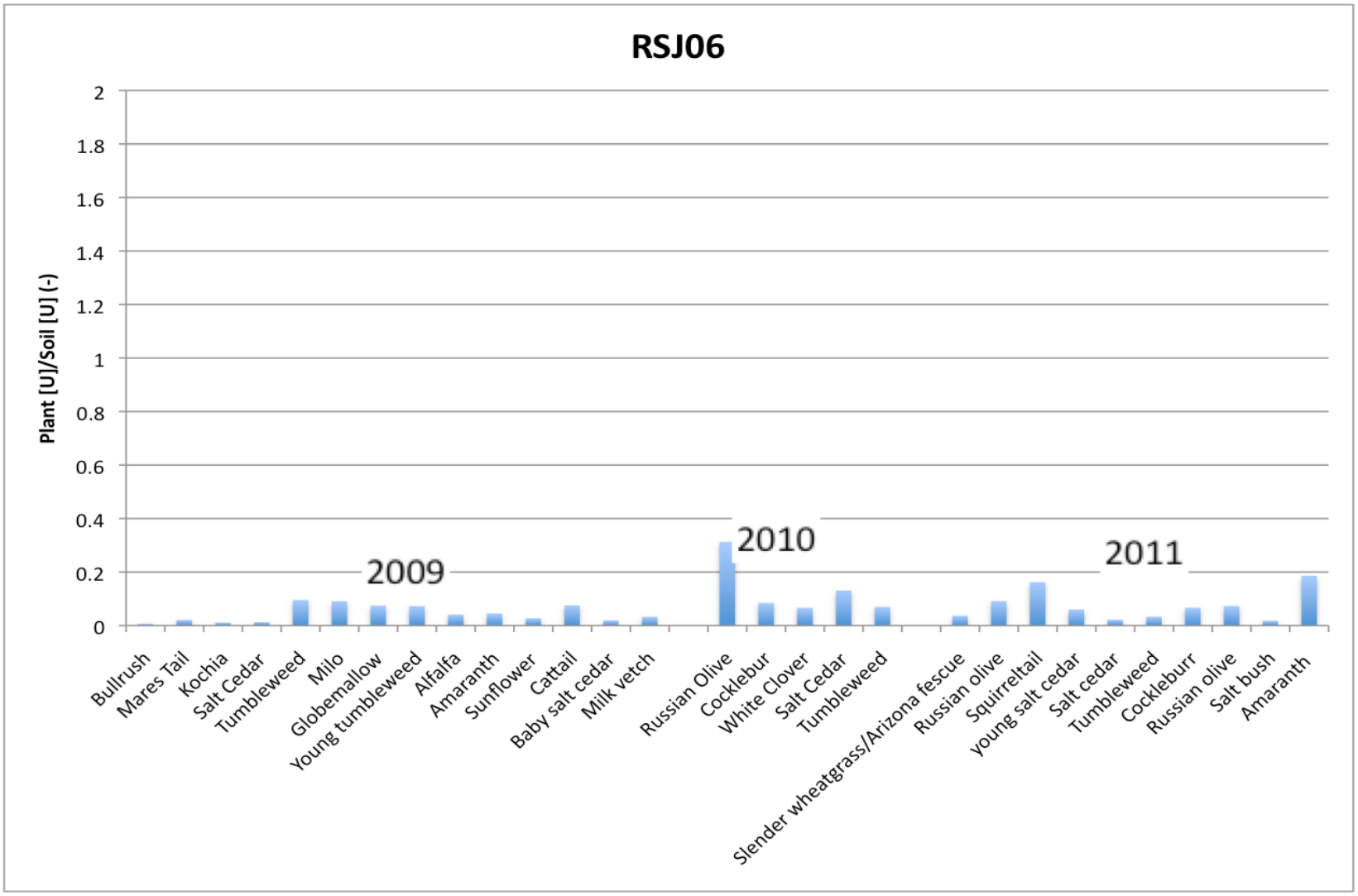


Figure 49. Ratios of plant U to soil U by plant at RSJ06 [ppm/ppm].

Finally, it is interesting to point out plant species that did not concentrate uranium above at least 1.0 ppm according to this study. Forbs in general did not seem to concentrate uranium very effectively. These included kochia, amaranth, sunflower, cocklebur, and aster. Highlighting the variability in uranium uptake by vegetation, plant species that had the highest uranium content were also found in the low uranium content bracket. These plants include: salt cedar, bulrush, cattails, tumbleweed, and Russian olive. While it is hypothesized that the plants growing in or near water were more likely to uptake higher levels of uranium, vegetation such as cottonwoods and watercress had relatively low uranium content (Appendix 3), but were found at the background site.

5.5 Soils

The Paguate Reservoir (RPG04) seems to act as a sediment trap and could be catching sediment upstream of the Mesita diversion at RSJ06. Uranium that is transported downstream would then be dissolved and reabsorbed by sediments. There does not appear to be a correlation between distance from the mine and uranium content. It was expected that the three sites would have decreasing values in uranium content corresponding to their distance from the mine. The assumption would be that RPG 03 at the exit of the mine would have the highest uranium content for soil, followed by RPG04, then RSJ06. As shown in Figure 50, RPG04 has the highest uranium content in soils followed by RPG03. As expected, RSJ06 has the lowest uranium content, although it has one of the single highest uranium levels for the study. One reason RPG04 could have higher uranium levels than soils on the Rio Paguate closer to the mine is that the reservoir offers a low energy environment for uranium bearing clays and fines to settle out. The RPG03 site is subject to high-velocity flows during monsoonal precipitation effects (pers.

comm.. C. Francisco, 9/7/11) and may essentially flush sediments downstream. Of course with every precipitation event, more uranium-laden sediments should be deposited at the RPG03 site, replenishing whatever was washed away. RPG03 also has higher sand content and lower clay content than RPG04, so perhaps this is contributing to the lower uranium content in the soils.

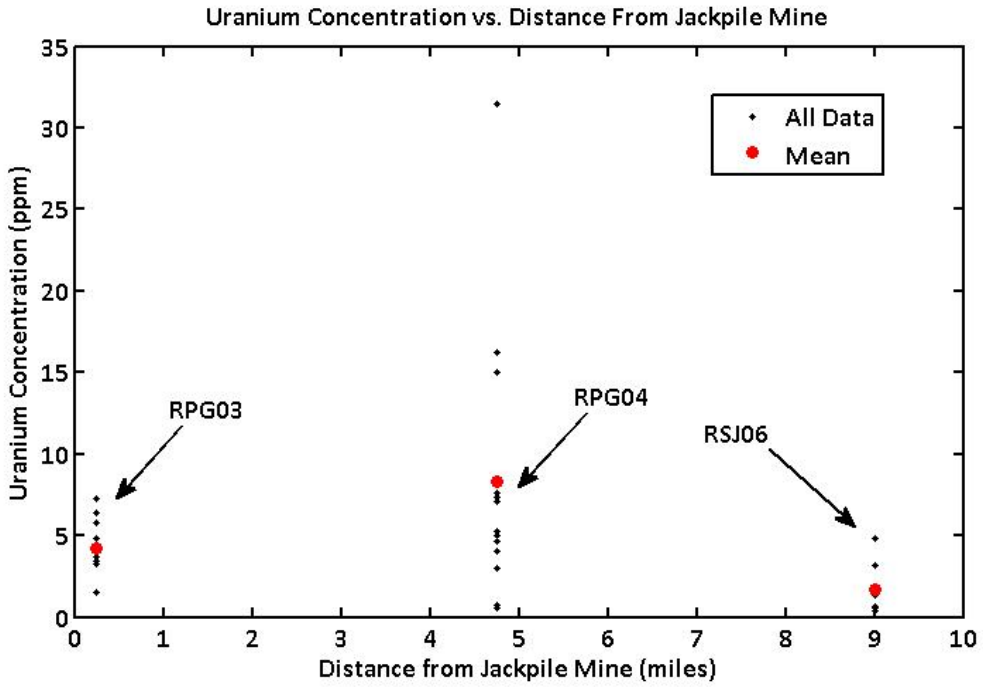


Figure 50. Plot showing uranium concentration as a function of distance from mine.

It appears that uranium complexes are being transported from the Jackpile Mine by surface waters to downstream areas of the Rio San Jose and Rio Paguate. One of the modes of transport is on colloidal particles that become incorporated into sediments behind the Mesita Diversion and in the Paguate Reservoir.

Comparison of average values for the Rio San Jose and Rio Paguate to crustal abundances is made in Table 6. The values reported by Brandvold et al. (1981) are much higher for uranium than any of the samples analyzed for this study. This could be because rates of pollution were higher in the late 1970's and early 1980's than they are right now, especially on the Rio San Jose. The Rio San Jose drains the western side of Mount Taylor and comprises the majority of the Grants Mineral Belt. Mortvedt (1994) noted that that bioavailability relies on the soil reaction affecting retention and solubility. In soils with low organic mater, U is able to be transported and may be able to pass through the soils (Mortvedt, 1994).

Table 6. Comparison of uranium concentration (ppm)

Sample Site	Uranium Concentration (Ave.)	Brandvold et al. (1981) Data	Crustal Abundance
RPG02	1.0832		2.7
RPG03	4.198		
RPG04	7.754		
RSJB	0.414		
RSJ06	1.739	267	

A connection between the depth of soil samples and their uranium content was not made. The plots in Appendix 5 show that uranium concentration varied between depths but not in any way that would suggest that uranium is higher at any specific depth for any of the sites.

5.6 Water

Not enough water samples were collected in this study to form a strong connection between the dissolved uranium in surface water and plant uranium concentration. Water data has been gathered by Laguna and shows that the total uranium concentration in the Rio San Jose and Rio Paguate is at times above the U.S. Environmental Protection Agency Maximum Contaminant Level of 0.03 ppm (USEPA, 2012).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This study was carried out to understand the mode of transport and storage sites for uranium downstream of the Jackpile Mine on the Rio San Jose and the Rio Paguate. The Jackpile Mine is not fully reclaimed and is now a source of uranium contamination to the surrounding communities and environment. Since the mid-1980's when a reclamation plan was being drawn up by the Anaconda Company who operated the mine, the Pueblo of Laguna and the Department of the Interior, there have been few studies of the environmental impacts of the mine on the Rio San Jose and Rio Paguate. Through cooperation between the Bureau of Geology and Mineral Resources and the Pueblo of Laguna, this study was carried out. With the assistance and guidance of the Pueblo of Laguna's Environmental Department, five sampling sites were chosen which included two sites that served as background, and three sites downstream of the Jackpile. The three sites ranged in distance from less than 0.5 mile from the mine's boundary, to approximately five miles downstream of the mine.

Soil samples were collected from various depths to determine if there was any leaching and deposition of uranium from the soil surface downward. Soil analyses showed that this was not the case. The soil samples were also subject to pipette analyses

to determine what, if any, effect clay content has on controlling soil uranium content. Results show that although there is a general trend of higher clay content in a soil sample with higher uranium content, this was not always the case. Of the three sites sampled downstream of the mine, RPG04, the Paguate Reservoir showed the highest uranium content in soils. The site farthest from the mine, RSJ06, had the lowest average uranium in soils. This may be due to dilution of uranium in sediments at RSJ06 which receives flow from the Rio Paguate and the Rio San Jose. The background sites appear to have lower values of uranium in soil, with RPG02 giving a more accurate description of what the natural background uranium soil content is in the study area.

Analyses show that, in general, uranium concentration in plants decreases with increasing distance downstream from the mine however, the Rio Paguate Reservoir serves as a trap for uranium particles that are made available to plant life. At every one of the sites, plants showed large variations in uranium content. The sight nearest the mine, RPG03, has lower uranium content in plants than RPG04. The sight farthest away from the mine, RPG06, has the lowest uranium concentration in plants. Most plants did not take up appreciable amounts of uranium. Plants with uranium concentration above 1.0 ppm were located at either RPG04 or RPG03 and included: salt cedar, white clover, cattails, bulrush, milo, prickly lettuce, an unidentified rush and an unidentified underwater grass.

Results of the ICP-MS analysis showed that there was a lot of variability between soils and plants, even at the same site. The reason for this is unclear, but may have to do on the amount of water the plant is able to draw through its roots.

The following are a number of recommendations for future work regarding the environmental impact of the Jackpile Mine:

The Jackpile Mine and the surrounding area could be the subject of a uranium phytoremediation study. Small plots constructed in situ along the Rio San Jose and Rio Paguate that include a variety of native vegetation, and weeds would allow for a better correlation between soils and uranium in plants. A single plot at a site could be treated with citric acid to facilitate the uptake of soluble uranyl ions into the roots to assess the use of soil amendments for potential phytoremediation in the area.

Soil-water could also be sampled with a small vacuum lysimeter in order to determine the chemistry of the soil water present after precipitation events. This would allow for a better understanding of what uranium is available to plants for uptake from the soil.

The water from the Rio San Jose and the Rio Paguate should have specific conductance and cation-anion analysis. Waters should also be analyzed and modeled to determine the soluble aqueous species of uranium in order to better assess the mobility paths of U pertaining to sediment leaching and remobilization potential. Remobilization of U into groundwater and surface water should be of great concern because of the potential to contaminate aquifers.

In the coming years, a heavier reliance on groundwater over dwindling surface supplies will require intensive monitoring of aquifer quality within the Laguna Reservation. Surface water is already fairly well monitored by the Pueblo itself. This program will need to extend to groundwater to detect the presence of any aquifer contamination from Jackpile and, possible plumes. Wells should also be installed in the

mine, in pits and protore dumps to monitor near what is more than likely the source of contamination.

The uranium that is being transported in airborne dust from the Jackpile Mine should also be investigated. The prevailing winds would need to be determined and then sampling sites for uranium concentration in the soil could be based off that. Further studies on soil could include the analysis of different soil particles sizes for uranium content. An ICP-MS study which analyzes clays to sands and coarser particles would be helpful in determining the extent clay content has on controlling uranium in sediments.

This study also brought up the need for more sampling of plants and water in the area. Surface water samplers consisting of PVC pipes with Nalgene bottles in them and then buried in a channel would allow for water samples to be taken during precipitation event without the need for personnel to be out in the field at those times.

BIBLIOGRAPHY

2012, Testimony on "HR 785, to amend the Surface Mining Control and Reclamation Act of 1977." House Committee on Natural Resources, Subcommittee on Energy & Mineral Resources. (http://democrats.naturalresources.house.gov/sites/democrats.naturalresources.house.gov/files/content/files/2012-02-17_HRG_EMR_Testimony_Luarkie.pdf.) (Accessed March 20, 2012).

Allen, W. C., Jordan, M. G., and Mills, S. L., 1986, Notice of Record of Decision on the Jackpile-Paguate Uranium Mine Reclamation, Albuquerque, NM, Bureau of Land Management and The Bureau of Indian Affairs.

Beck, R. G., Cherrywell, C. H., Earnest, D. F., and Feirn, W. C., 1980, Jackpile-Paguate Deposit, *in* Rautman, C. A., ed., Geology and mineral technology of the Grants uranium region 1979; pp. 269-275.

Boyle, G. J., 1976, Uranium industry in New Mexico: New Mexico Energy Research and Development Institute, NMERDI 2-65-1100B, ERB 76-100B, 143 p.

Brandvold, D. K., Popp, C. J., and Brandvold, L., 1981, Transport Mechanisms in sediment Rich Streams Heavy Metal and Nutrient Load of the Rio San Jose-Rio Puerco Systems: New Mexico Water Resources Research Institute, Project No. B-062 NMEX, 30 p .

Brierly, C.L., Brierly, J.A., 1981, Contamination of ground and surface waters due to uranium mining and milling, Volume 1: U.S. Bureau of Mines, Washington D.C., 102 p.

Carvalho, I. G., Cidu, R., Fanfani, L., Pitsch, H., Beaucaire, C., and Zuddas, P., 2005, Environmental impact of uranium mining and ore processing in the Lagoa Real District, Bahia, Brazil: Environmental Science and Technology, no. 39, pp. 8646-8652.

Dunmire, W. W., and Tierney, G., 1995, Wild plants of the Pueblo Province: Exploring ancient and enduring uses: Santa Fe, Museum of New Mexico Press. p.10.

Ebbs, S. D., Brady, D. J., and Kochian, L. V., 1998, Role of uranium speciation in the uptake and translocation of uranium by plants: Journal of Experimental Botany, v. 49, no. 324, pp. 1183-1190.

Eisenbud, M., Gesell, T., 1997, Environmental radioactivity from natural, industrial, and military sources, Academic Press: San Diego, 656 p.

Graf, W. L., 1994, Plutonium and the Rio Grande: Environmental change and contamination in the nuclear age, New York, Oxford University Press, pp. 45-126.

Fitch, A.J., Herndon, J.P., 1957, Anaconda's Jackpile Mine: Mining Congress and Journal, v. 43, no. 6, p. 57-60.

Hatchell, B., and Wentz, C., 1981, Uranium Resources and Technology 1980: A review of the New Mexico uranium industry, 226 p.

Hawley, J. W., Crumpler, L. S., and Wells, S. G., 1982, Road Log Segment II-B: I-40/N.M. 6 interchange to La Jara Mesa Northwest of Mount Taylor via Laguna,

Paguate, El Malpais and Grants, *in* Grambling, J. A., and Wells, S. G., eds., Albuquerque Country II, New Mexico Geological Society, pp. 49-70.

Holmquist, R. J., 1970, The discovery and development of uranium in the Grants Mineral Belt, New Mexico. U.S. A.E.C Report RMF 172, pp. 98-101.

Hoppe, 1978, A stretch of desert along Route 66-the Grants belt-is chief locale for US uranium: Engineering and Mining Journal, no. 179, p. 73.

Hough, H. W., 1955, The team that found the Jackpile Mine, Uranium Magazine, v. 1, pp. 6-8.

The Jackpot at Jackpile is still paying off: Engineering and Mining Journal, 1978, no. 179, pp. 86-90.

Kittel, D. F., 1963, Geology of the Jackpile Mine area, *in* Kelley, V.C., ed., Geology and Technology of the Grants Uranium Region, New Mexico Bureau of Mines & Mineral Resources Memoir 15, pp. 167-176.

Kittel, D. F., Kelley, V. C., and Melancon, P. E., 1967, Uranium Deposits of the Grants Region, *in* Trauger, F.D., ed., Defiance-Zuni-Mt. Taylor Region, Eighteenth Field Conference, New Mexico Geological Society, pp. 173-183.

Kuykendall, S. T., 2006, Phytoremediation of depleted uranium-contaminated high desert mountain soil using caladium and perennial plants [Master of Science: New Mexico Institute of Mining and Technology], 94 p.

Love, D. W., 1989, Geomorphic development of the Rio San Jose Valley, *in* Anderson, O. J., Lucas, S. G., Love, D. W., and Cather, S. M., eds., Southeastern Colorado Plateau, New Mexico Geological Society, pp. 11-12.

Smith, Jr., M.C., 1967, The AEC and the Grants Mineral Belt, *in* Trauger, F.D, ed.,

Defiance-Zuni-Mt. Taylor Region, Eighteenth Field Conference, New Mexico Geological Society, pp. 184-187.

Markich, S. J., 2002, Uranium speciation and bioavailability in aquatic systems: An overview: The Scientific World Journal, v. 2, pp. 707-729.

Mason, C. F. V., Turney, W. R. J. R., Thomson, B. M., Lu, N., Longmire, P. A., and Chisholm-Brause, C. J., 1997, Carbonate leaching of uranium from contaminated soils: Environmental Science and Technology, v. 31, no. 10, pp. 2707-2711.

McLemore, V., 2007, Uranium resources in New Mexico, SME Annual Meeting: Denver, CO, pp. 2-4

Miera, Jr., F.R., 1980, Measurements of uranium in soils and small mammals [Master of Science: University of California, Los Alamos Scientific Laboratory, pp. 3-7.

Miller, J. R., and Wells, S. G., 1986, Types and processes of short-term sediment and uranum-tailings storage in arroyos: an example from the Rio Puerco of the West, new Mexico, *in* Proceedings Drainage Basin Sediment Delivery, Albuquerque, New Mexico, pp. 335-353.

Moench, R. H., and Schlee, J. S., 1967, Geology and uranium deposits of the Laguna District, New Mexico, Washington D.C., United States Government Printing Office, Geological Survey Professional Paper 519, 114 p.

Mortvedt, J.J., 1994, Plant and soil relationships of uranium and thorium decay series radionuclides-A review Journal of Environmental Quality, v. 23, pp. 643-650.

Murphy, W. M., and Shock, E. L., 1999, Environmental aqueous geochemistry of actinides, *in* Burns, P. C., and Finch, R., eds., Uranium: Mineralogy, geochemistry and the environment, Mineralogical Society of America, v. 38, pp.

221-253.

Nash, J. T., 1968, Uranium deposits in the Jackpile sandstone, New Mexico: Economic Geology, v. 63, pp. 737-750.

Neves, M. O., Abreu, M. M., and Figueiredo, V., 2012, Uranium in vegetable foodstuffs: should residents near the Cunha Baixa uranium mine site (Central Northern Portugal) be concerned?: Environmental Geochemistry and Health, v. 34, pp. 181-189.

N.M. mine could be superfund site, (2012, March 14), Albuquerque *Journal*, p.c1.

Novo-Gradac, K. J., 1983, Trace metal and radionuclide distributions in recent sediments of the Rio Puerco, Rio San Jose, and Paguate Reservoir in the Grants Mineral Belt [Master of Science: New Mexico Institute of Mining and Technology], 125 p.

O'Brien, K., and Associates, 1975, Flood Plain Information Rio San Jose, Pueblo of Laguna, New Mexico: Department of the Army, Albuquerque District, Corps of Engineers, 30 p.

Olsson, W. A., Lorenz, J. C., and Cooper, S. P., 2004, A mechanical model for multiply-oriented conjugate deformation bands: Journal of Structural Geology, v. 26, no. 2., p. 327.

Popp, C. J., Hawley, J. H., Love, D. W., and Dehn, M., 1988, Use of Radiometric (Cs-137, Pb-210), Geomorphic, and Stratigraphic Techniques to Date Recent Oxbow Sediments in the Rio Puerco Drainage Grants Uranium Region, New Mexico: Environmental and Geological Water Science, v. 11, no. 3, pp. 253-269.

Rautman, C., 1977, The uranium industry in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Report 74, 23 p.

Reith, C. C., Portillo, R., Millard, J., and Gonzales, D., 1990, Cost Optimization on the Jackpile-Paguate Reclamation Program, *in* Doyle, F. M., ed., Western Regional Symposium on Mining & Mineral Processing Wastes, Volume Mining and Mineral Processing Wastes: Berkeley, California, Society for Mining, Metallurgy and Exploration, pp. 181-184.

Risser, D. W., and Lyford, F. P., 1983, Water resources on the Pueblo of Laguna, West-Central New Mexico: U.S. Geological Survey. Water-Resources Invesigations Report 83-4038, pp. 10-22.

US Department of the Interior, 1985, Jackpile-Paguate Uranium Mine Reclamation Project Environmental Impact Statement, February 1985.

US Environmental Protection Agency, 2012, HRS Documentation Record. (http://www.epa.gov/superfund/sites/docrec/pdoc1865.pdf). Accessed August, 2012.

US Environmental Protection Agency, 2012, 2012 Edition of the drinking water standards and health advisories. (http://water.epa.gov/action/advisories/drinking/upload/dwstandards2012.pdf). Accessed April 10, 2013.

Whicker, F. W., and Schultz, V., 1982, Radioecology: nuclear energy and the environment, Boca Raton, Florida, CRC Press, pp. 159-160.

Zielinski, R. A., Otton, J. K., Schumann, R. R., and Wirt, L., 2008, Uranium in surface waters and sediments affected by historical mining in the Denver West 1:100,000 Quadrangle, Colorado: United States Geological Survey. (http://pubs.usgs.gov/sir/2007/5246/508ZielinskiSIR07_5246.pdf). (Accessed

May, 2010).

Zimmermann, C.F., 1979, Uranium resources on federal lands, Lexington Books, 326 p.

APPENDIX 1. Seed Mixture for the Jackpile-Paguate Reclamation Project (Reith et al., 1993).

Genus and Species	Common Name	Mixture (%)
Bouteloua gracilia	Blue grama	30
Sporoblous cryptandius	Sand dropseed	15
Bouteloua curtipendula	Sideoats grama	4
Sporobolus airoides	Alkali sacaton	5
Oryzopsis hymenoides	Indian ricegrass	5
Eragrostis curvula	Weeping lovegrass	10
Atriplex canescens	Fourwing saltbush	15
Agropyron smithii	Western wheatgrass	5
Erotia lanata	Winterfat	6
Melilotus officinalis	Sweetclover	5

APPENDIX 2. Uranium concentration for soil samples and results of pipette analysis.

Sample #:	Sample Name:	Sampling Site	Depth (in.)	Date collected	Uranium - 238 (ppm)	Soil Classification	Sand (%)	Silt (%)	Clay (%)
RSJ06-1s	RSJ06-1S 0-6" Top	Mesita Dam	6	8/19/09	0.3709	Si	0.1	27.6	72.3
RSJ06-2s	RSJ06-2S 0-6" Bottom	Mesita Dam	12	8/19/09	3.204	Si	0.8	33.5	65.7
RSJ06-5s	RSJ06 Black Goo	Mesita Dam	<6	8/19/09	4.827	Si	0.1	26.3	73.6
0525N21	RSJ06 N Bank 0-6"	Mesita Dam	6	9/15/10	0.6054	S	89.3	4.3	6.4
0525N25	RSJ06 N Bank 6-12"	Mesita Dam	12	9/15/10	1.373	LS	79.9	8.2	12.0
0525N20	RSJ06 S Bank 6-12"	Mesita Dam	12	9/15/10	1.616	SiC	16.9	29.1	54.0
0525N19	RSJ06 S Bank 0-6"	Mesita Dam	6	9/15/10	1.762	SiC	1.9	31.5	66.6
012412P18	RSJ06 Channel	Mesita Dam	<6	6/1/11	1.807	SiC	8.5	20.1	71.4
012412P19	RSJ06 S Bank 0-6"	Mesita Dam	6	6/1/11	1.596	SiC	4.3	27.3	68.4
012412P20	RSJ06 S Bank 6-12"	Mesita Dam	12	6/1/11	0.6596	SC	90.1	4.2	5.7
013112P32	RSJ06 N Bank 0-6"	Mesita Dam	6	6/1/11	1.446	CL	73.9	7.5	18.6
013112P31	RSJ06 N Bank 6-12"	Mesita Dam	12	6/1/11	1.599	C	3.4	31.5	65.1
RPG04b-4s	RPG04b 0-6" Bottom	Paguate Reservoir	12	8/19/09	14.98	SCl	34.0	29.8	36.2
RPG04b-3s	RPG04b 0-6" Top	Paguate Reservoir	6	8/19/09	31.44	SCl	32.7	28.8	38.5
012412P17	RPG04 Reservoir bottom	Paguate Reservoir	<6	6/1/11	16.21	SiC	7.8	41.5	50.7
0525N16	RPG04 Channel	Paguate Reservoir Channel	<6	9/15/10	3.004	S	86.9	8.3	4.8
0525N17	RPG 04 N Bank 0-6"	Paguate Reservoir Channel	6	9/15/10	5.04	SiC	2.5	46.6	50.8
0525N14	RPG04 S Bank 0-6"	Paguate Reservoir Channel	6	9/15/10	5.256	SiC	3.5	48.6	47.9
0525N18	RPG04 N Bank 6-12"	Paguate Reservoir Channel	12	9/15/10	7.067	SiC	2.7	53.1	44.2
0525N15	RPG04 S Bank 6-12"	Paguate Reservoir Channel	12	9/15/10	7.377	SiC	2.9	53.7	43.4
012412P13	RPG04 S Bank 0-6"	Paguate Reservoir Channel	6	6/1/11	4.083	S	4.1	44.1	51.8
012412P14	RPG04 S Bank 6-12"	Paguate Reservoir Channel	12	6/1/11	0.7384	SiCL	88.9	2.9	8.2
012412P15	RPG04 N Bank 0-6"	Paguate Reservoir Channel	6	6/1/11	4.645	SiL	2.5	42.1	55.4
012412P16	RPG04 N Bank 6-12"	Paguate Reservoir Channel	12	6/1/11	7.644	CL	17.8	51.9	30.3
012412P9	RPG04 Channel	Paguate Reservoir Channel	<6	6/1/11	0.5486	S	89.2	2.4	8.4
0525N1	RPG02 S Bank 0-6"	Rio Paguate Background	6	9/15/10	1.01	S	82.1	9.7	8.2
0525N3	RPG02 Channel	Rio Paguate Background	<6	9/15/10	1.079	S	77.8	12.8	9.3
0525N2	RPG02 S Bank 6-12"	Rio Paguate Background	12	9/15/10	1.132	LS	71.8	18.6	9.6
0525N5	RPG02 N Bank 6-12"	Rio Paguate Background	12	9/15/10	1.337	LS	77.2	13.3	9.5
0525N4	RPG02 N Bank 0-6"	Rio Paguate Background	6	9/15/10	1.355	S	78.7	12.1	9.3
012412P1	RPG02 Channel	Rio Paguate Background	<6	6/1/11	0.8589	LS	71.3	18.1	10.6
012412P2	RPG02 S Bank 0-6"	Rio Paguate Background	6	6/1/11	1.092	SL	61.0	25.0	14.0
012412P3	RPG02 S Bank 6-12"	Rio Paguate Background	12	6/1/11	0.8593	SL	69.2	18.2	12.6
012412P4	RPG02 N Bank 0-6"	Rio Paguate Background	6	6/1/11	1.026	LS	62.6	23.4	14.0
0525N6	RPG03 W Bank 0-6"	RP-Exit of mine	6	9/15/10	1.542	S	71.4	19.1	9.5
0525N7	RPG03 W Bank 6-12"	RP-Exit of mine	12	9/15/10	4.797	S	85.6	8.4	6.0
0525N8	RPG03 E Bank 0-6"	RP-Exit of mine	6	9/15/10	5.83	L	58.0	34.8	7.2
0525N13	RPG03 Channel	RP-Exit of mine	<6	9/15/10	6.398	SiC	3.3	78.0	18.7
0525N9	RPG03 E Bank 6-12"	RP-Exit of mine	12	9/15/10	7.243	SL	66.5	28.8	4.7
012412P5	RPG03 E Bank 0-6"	RP-Exit of mine	6	6/1/11	3.711	SL	70.0	19.3	10.7
012412P6	RPG03 E Bank 6-12"	RP-Exit of mine	12	6/1/11	3.397	SL	67.1	20.8	12.1
012412P7	RPG03 W Bank 0-6"	RP-Exit of mine	6	6/1/11	1.563	LS	68.3	21.8	9.8
012412P8	RPG03 W Bank 6-12"	RP-Exit of mine	12	6/1/11	3.304	S	81.6	11.0	7.3
0525N26	RSJB Channel	RSJ Background	<6	9/15/10	0.5491	S	96.4	3.6	0.0
013112P33	RSJB Channel	RSJ Background	<6	6/1/11	0.3218	S	96.5	2.6	0.9
013112P34	RSJB S Bank	RSJ Background	<6	6/1/11	0.3713	S	93.8	3.2	3.0

APPENDIX 3. 2009-2011 Plant analysis for uranium.

Sample Name:	Common Name:	Date Collected	Uranium (238), (mg/kg)
	RPG02		
RPG02-72210-1	Alder	7/22/10	0.16
RPG02-72210-2	Oatgrass	7/22/10	0.10
RPG02-72210-3	Lambs Ear	7/22/10	0.16
RPG02-72210-4	Watercress	7/22/10	0.31
RPG02-72210-5	Unidentified grass	7/22/10	0.08
RPG02-72210-6	Red Plantain	7/22/10	0.33
RPG02-6111-1	Alfalfa	6/1/11	0.06327
RPG02-6111-2	Bentgrass	6/1/11	0.1183
RPG02-6111-3	Bluegrass	6/1/11	0.202
RPG02-6111-4	Meadowrue	6/1/11	0.09851
RPG02-6111-5	Cutleaf Coneflower	6/1/11	0.1071
RPG02-6111-6	Spotted Water Hemlock	6/1/11	0.1421
	RSJB		
RSJB-72210-20	Salt Cedar	7/22/10	0.53
RSJB-72210-21	Russian Olive	7/22/10	0.60
RSJB-72210-22	Native Bamboo	7/22/10	0.87
RSJB-72210-23	Cocklebur	7/22/10	0.47
RSJB-72210-24	Koscia	7/22/10	0.15
RSJB-6111-20	Sacoton ?	6/1/11	0.1078
RSJB-6111-21	Bullrush	6/1/11	0.06329
RSJB-6111-22	Wooly indian wheat	6/1/11	0.08426
RSJB-6111-23	cottonwood	6/1/11	0.09789
RSJB-6111-24	koscia	6/1/11	0.1172
RSJB-6111-25	young tumbleweed	6/1/11	0.05692
RSJB-6111-26	Japanese brome	6/1/11	0.3299
RSJB-6111-27	Western wheatgrass	6/1/11	0.05464
RSJB-6111-28	Squirreltail	6/1/11	0.3244
RSJB-6111-29	unidentified phlox	6/1/11	0.03028
RSJB-6111-30	letuca virosa	6/1/11	0.08062
RSJB-102511-1	Unknown kale-like plant	10/25/11	0.3417
RSJB-102511-2	Willow	10/25/11	0.2066
RSJB-102511-3	Koscia	10/25/11	0.0706
RSJB-102511-5	cottonwood	10/25/11	0.2682
RSJB-102511-5	Western wheatgrass	10/25/11	0.2467
RSJB-102511-6	Sand dropseed?	10/25/11	0.1976
	RPG03		
RPG03-72210-7	Cattail	7/22/10	0.89
RPG03-72210-8	Salt Cedar	7/22/10	3.02
RPG03-72210-9	White Clover	7/22/10	0.76
RPG03-72210-10	Russian Olive	7/22/10	0.74
RPG03-6111-7	young vine mesquite	6/1/11	0.8794
RPG03-6111-8	koscia	6/1/11	0.6606
RPG03-6111-9	Alfalfa	6/1/11	0.7062
RPG03-6111-10	Russian olive	6/1/11	0.6424
RPG03-6111-11	young salt cedar	6/1/11	0.5005
RPG03-6111-12	Bullrush	6/1/11	3.432

RPG03-6111-13	Cattail	6/1/11	2.611
RPG03-102511-7	Willow	10/25/11	0.6915
RPG03-102511-8	RabbitBrush	10/25/11	0.3494
RPG03-102511-9	Cattail	10/25/11	0.7115
RPG03-102511-10	White clover	10/25/11	1.638
	RPG04		
RPG04-0809-7-A1	Salt Cedar	8/19/09	0.02
RPG04-0809-5A-A3	Russian Olives (leaves)	8/19/09	0.01
RPG04-0809-5-A8	Russian Olive (olives)	8/19/09	0.00
RPG04-0809-7-B1	Salt Cedar	8/19/09	0.01
RPG04-0809-5A-B3	Russian Olives (leaves)	8/19/09	0.00
RPG04-0809-5A-B10	Russian Olives (leaves)	8/19/09	0.00
RPG04-0809-5-B8	Russian Olive (olives)	8/19/09	0.00
RPG04-0809-7	Salt Cedar	8/19/09	3.62
RPG04-0809-5A	Russian Olive leaves	8/19/09	0.89
RPG04-0809-5	Russian Olive olives	8/19/09	0.06
RPG04-0809-1	Aster daisy	8/19/09	0.41
RPG04-0809-2	Cattail	8/19/09	0.99
RPG04-0809-3	Sedge	8/19/09	1.06
RPG04-0809-6	Salt Cedar	8/19/09	3.37
RPG04-0809-4	Native Bamboo	8/19/09	0.14
RPG04-72210-11	Cattail	7/22/10	0.29
RPG04-72210-12	Russian Olive	7/22/10	0.22
RPG04-72210-13	Salt Cedar	7/22/10	1.53
RPG04-72210-14	Unidentified Rush	7/22/10	5.53
RPG04-102511-11	Prickly Lettuce	10/25/11	7.495
RPG04-102511-12	underwater grass	10/25/11	23.62
RPG04-102511-13	Cattails	10/25/11	4.007
RPG04-102511-14	Milo	10/25/11	6.286
	RSJ06		
RSJ06-0809-2-A10	Bullrush	8/19/09	0.00
RSJ06-0809-2-A2	Bullrush	8/19/09	0.00
RSJ06-0809-16-A5	Mares Tail	8/19/09	0.00
RSJ06-0809-15-A6	Koscia	8/19/09	0.00
RSJ06-0809-3-A7	Salt Cedar	8/19/09	0.00
RSJ06-0809-2-B2	Bullrush	8/19/09	0.00
RSJ06-0809-16-B5	Mares Tail	8/19/09	0.00
RSJ06-0809-15-B6	Koscia	8/19/09	0.00
RSJ06-0809-3-B7	Salt Cedar	8/19/09	0.00
RSJ06-0809-2	Bullrush	8/19/09	0.03
RSJ06-0809-16	Mares Tail	8/19/09	0.10
RSJ06-0809-15	Koscia	8/19/09	0.05
RSJ06-0809-3	Salt Cedar	8/19/09	0.06
RSJ06-0809-1	Tumbleweed	8/19/09	0.46
RSJ06-0809-12	Milo on fill	8/19/09	0.29
RSJ06-0809-13	Globemallow	8/19/09	0.36
RSJ06-0809-14	Young tumbleweed	8/19/09	0.35
RSJ06-0809-4	Alfalfa	8/19/09	0.20
RSJ06-0809-5	Amaranth	8/19/09	0.24

RSJ06-0809-6	Sunflower	8/19/09	0.13
RSJ06-0809-7	Amaranth	8/19/09	0.19
RSJ06-0809-8	Cattail	8/19/09	0.36
RSJ06-0809-9	Baby salt cedar	8/19/09	0.09
RSJ06-0809-10	Milk vetch	8/19/09	0.16
RSJ06-0809-11	Milo	8/19/09	0.59
RSJ06-72210-15	Russian Olive	7/22/10	0.55
RSJ06-72210-16	Cocklebur	7/22/10	0.15
RSJ06-72210-17	White Clover	7/22/10	0.12
RSJ06-72210-18	Salt Cedar	7/22/10	0.23
RSJ06-72210-19	Tumbleweed	7/22/10	0.12
RSJ06-6111-14	Amaranth (bank)	6/1/11	0.2691
RSJ06-6111-15	Amaranth (channel)	6/1/11	0.09293
RSJ06-6111-16	Slender wheatgrass/Arizona fescue	6/1/11	0.05803
RSJ06-6111-17	Russian olive	6/1/11	0.1458
RSJ06-6111-18	Squirreltail	6/1/11	0.2587
RSJ06-6111-19	young salt cedar	6/1/11	0.09604
RSJ06-102511-15	Salt cedar	10/25/11	0.03516
RSJ06-102511-16	Tumbleweed	10/25/11	0.05295
RSJ06-102511-17	Cockleburr	10/25/11	0.1067
RSJ06-102511-18	Russian olive	10/25/11	0.117
RSJ06-102511-19	salt bush	10/25/11	0.02889

APPENDIX 4. All available water data collected for this study.

Sample Name:	RSJ06	RPG04	RPG02-091510	RPG03-091510	RPG04-091510	RSJ06-091510
Year	2009	2009	2010	2010	2010	2010
pH	8.7	8.0	8.2	8.1	7.9	8.1
Conductivity (uS/cm)	7340	7400	3460	5610	1720	5740
Alkalinity as $CO3^{-2}$ (mg/L)	5.8					
Alkalinity as HCO3- (mg/L)	145	455	195	395	295	395
Bromide (mg/L)	2.7	1.9	<0.1	0.62	<0.2	1.5
Chloride (mg/L)	690	120	4.5	68	18	430
Fluoride (F-) (mg/L)	<1.0	1.18	0.25	0.75	0.75	0.85
Nitrite (NO2-) (mg/L)	<1.0	<1.0	<0.1	<0.5	<0.2	<0.5
Nitrate (NO3-) (mg/L)	<1.0	<1.0	<0.1	<0.5	<0.2	<0.5
Phosphate (mg/L)	<5.0	<5.0	<0.5	<2.5	<1.0	<2.5
Sulfate (SO42-) (mg/L)	3090	4320	10	3180	685	2300
Sodium (Na) (mg/L)	1245	1030	16	695	105	890
Potassium (K) (mg/L)	20	22	4.7	16	20	14
Magnesium (Mg) (mg/L)	320	450	13	395	62	190

Calcium (Ca) (mg/L)	225	545	34	345	200	270
Total cations (meq/L)	92.24	109.58	3.57	80.36	20.15	68.18
Total anions (meq/L)	86.40	100.88	3.55	74.65	19.63	66.55

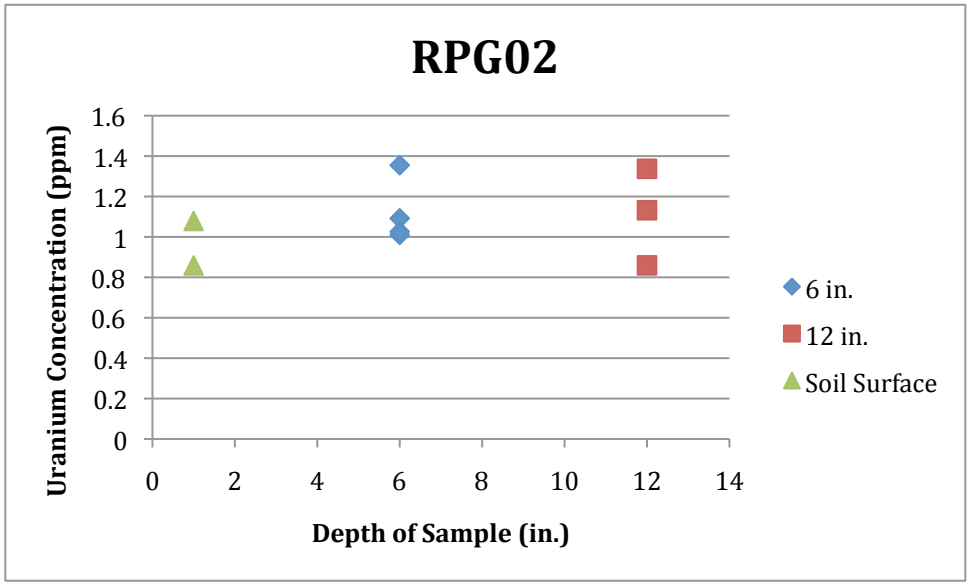
Percent difference	3.27	4.13	0.25	3.68	1.31	1.21
TDS calculated (mg/L) **	5678	6731	230	4910	1262	4306
Hardness (mg eq/L CaCO3)	1880	3215	137	2488	755	1457
SiO2 calculation (mg/L)	1.1	3.3	49	4.8	22	5.6
Aluminum (Al)	0.055	<0.02	0.044	0.21	0.028	0.13
Antimony (Sb)	<0.1	<0.1	<0.005	<0.050	<0.050	<0.050
Arsenic (As)	<0.02	<0.02	0.002	<0.010	<0.010	<0.010
Barium (Ba)	0.12	<0.1	0.033	0.066	<0.050	0.10
Beryllium (Be)	<0.02	<0.02	<0.001	<0.010	<0.010	<0.010
Boron (B)	1.3	0.58	0.019	0.36	0.14	0.91
Cadmium (Cd)	<0.02	<0.02	<0.001	<0.010	<0.010	<0.010
Chromium (Cr)	<0.02	<0.02	<0.001	<0.010	<0.010	<0.010
Cobalt (Co)	<0.02	<0.02	<0.001	<0.010	<0.010	<0.010
Copper (Cu)	0.027	0.074	<0.001	<0.010	<0.010	<0.010
Lead (Pb)	0.036	<0.02	<0.001	<0.010	<0.010	<0.010
Lithium (Li)	1.0	0.16	0.007	0.11	0.029	0.58
Manganese (Mn)	0.28	0.26	0.023	0.15	0.11	0.38
Molybdenum (Mo)	<0.02	<0.02	0.001	<0.010	<0.010	<0.010
Nickel (Ni)	<0.02	<0.02	<0.001	<0.010	<0.010	<0.010
Selenium (Se)	<0.1	<0.1	<0.005	<0.050	<0.050	<0.050
Silicon (Si)	<0.5	1.5	23	2.5	10	2.8
Silver (Ag)	<0.02	<0.02	<0.001	<0.010	<0.010	<0.010
Strontium (Sr)	5.5	10	0.22	6.9	2.2	5.6
Thallium (Tl)	<0.02	<0.02	<0.001	<0.010	<0.010	<0.010

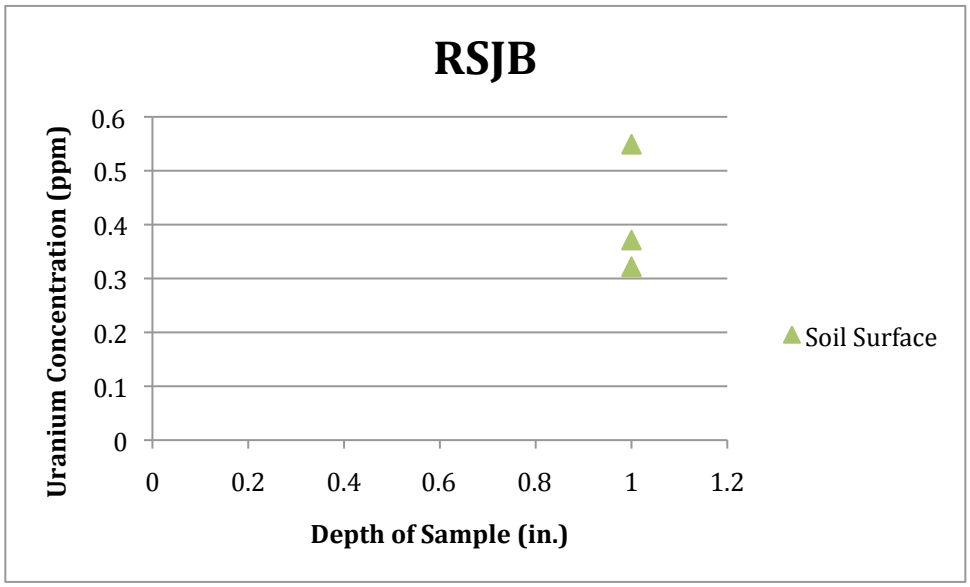
Thorium (Th)	<0.02	<0.02	<0.001	<0.010	<0.010	<0.010
Tin (Sn)	<0.02	<0.02	<0.001	<0.010	<0.010	<0.010
Titanium (Ti)	<0.02	<0.02	0.005	<0.010	<0.010	<0.010
Uranium (U)	<0.02	0.098	<0.001	0.46	0.021	0.005
Vanadium (V)	<0.02	<0.02	0.004	<0.010	<0.010	<0.010
Zinc (Zn)	0.035	0.023	<0.001	<0.010	<0.010	<0.010

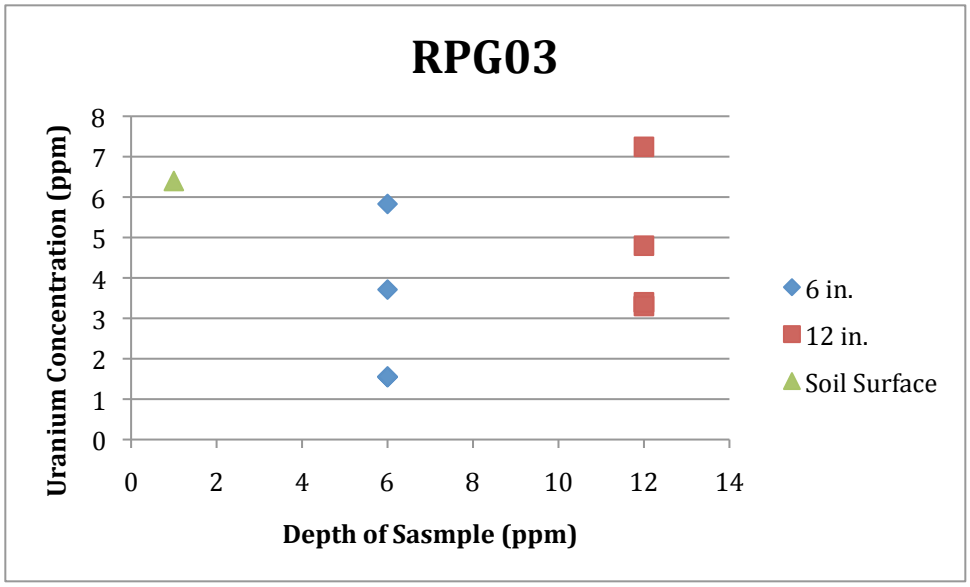
ICP-OES

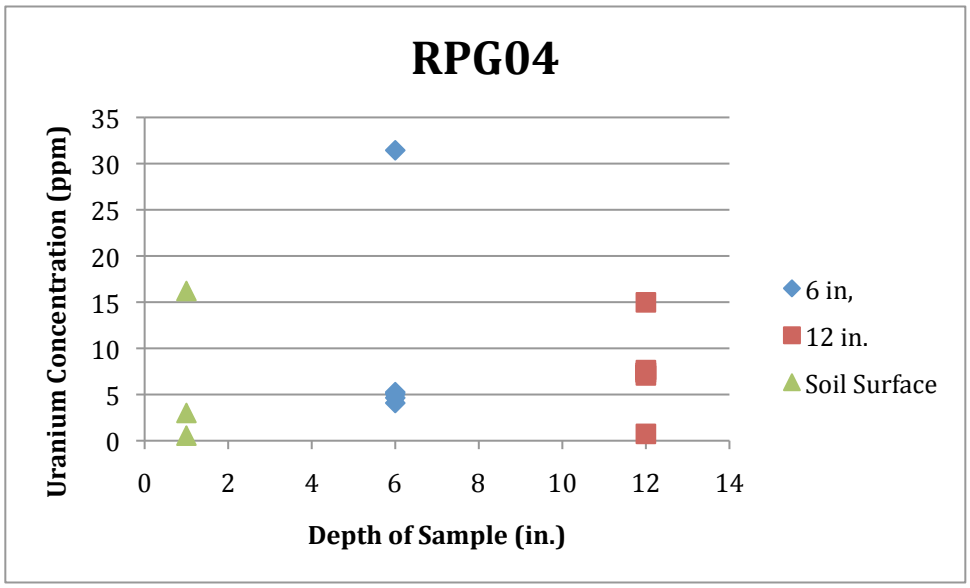
Iron (Fe)	<0.05	<0.05	0.15	0.28	0.37	0.21
Silicon (Si)	<2	<2				

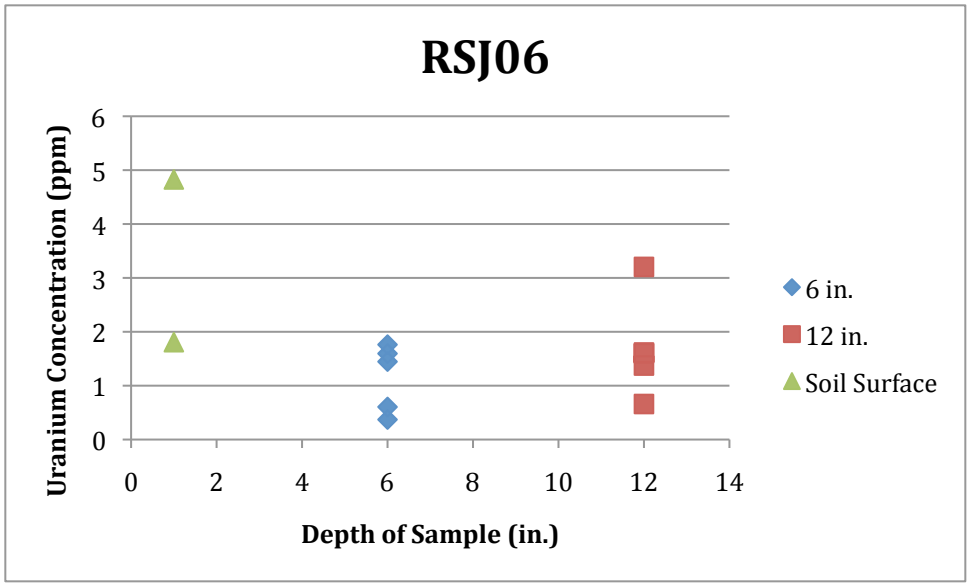
APPENDIX 5. Plots of depth of soil samples versus uranium concentration.






RPG03
Uranium Concentration (ppm)
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10
12
14
Depth of Sasmple (ppm)
6 in.
12 in.
Soil Surface


RPG04
Uranium Concentration (ppm)
0
5
10
15
20
25
30
35
0
2
4
6
8
10
12
14
Depth of Sample (in.)
6 in,
12 in.
Soil Surface


RSJ06
Uranium Concentration (ppm)
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
Depth of Sample (in.)
6 in.
12 in.
Soil Surface

APPENDIX 6. Photos of sample sites.

RPG02- Rio Paguate Background

RSJB- Rio San Jose Background

RPG03- Rio Paguate downstream Jackpile Mine

RPG04- Rio Paguate Reservoir

RSJ06- Rio San Jose near Mesita, NM