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Estimating Aquifer Characteristics and Identification of a Sub-Basin for Artificial Storage and Recovery, Northeastern Ivanpah Valley, Nevada

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ABSTRACT

Estimating Aquifer Characteristics and Identification of a Sub-basin for Artificial Storage and Recovery, Northeastern Ivanpah Valley, Nevada.

by
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The identification of a structurally controlled sub-basin with impediments to groundwater flow within Southern Nevada could provide a favorable area for artificial recharge and storage of native or imported water, extending the water supply of Southern Nevada. For this purpose, the area of northeastern Ivanpah Valley was investigated to determine the ability of the aquifer to accept and recover stored water, if acceptable water quality existed in the potential sub-basin storage area, and if structural controls impeded and isolated groundwater flow. The results found evidence the proposed sub-basin is structurally isolated by the McCullough, Roach, and Stateline Faults, which was determined by field mapping, groundwater geochemistry, and stable and radiometric isotope data. Aquifer data of hydraulic conductivity, transmissivity, specific yield, and specific capacity compiled from previous studies also indicated the northern portion of Ivanpah Valley would meet the basic requirements for artificial storage and recovery of groundwater, either via injection wells or infiltration basins. The sub-basin identified during this research was found to have degraded groundwater quality not acceptable for artificial water storage and recovery operations. Based upon the native groundwater quality of the sub-basin, artificial recharge operations in Ivanpah Valley should occur outside of the identified sub-basin, within the main portions of the valley. Further hydrogeologic study is needed to understand groundwater interaction across these impediments dividing the sub-basin and the remainder of Ivanpah Valley before artificial recharge and recovery operations occur.

ACKNOWLEDGEMENTS

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LIST OF ACROMYMS AND ABREVIATIONS

AFY	- Acre foot per year
AMSL	- Above mean sea level
ASR	- Artificial Storage and Recovery
BGS	- Below ground surface
BYU	- Brigham Young University
CADWR	- California Department of Water Resources
cm	- Centimeter
EPA	- US Environmental Protection Agency
ft	- Foot
gal	- Gallon
gpm	- Gallons per minute
HA	- Hydrographic Area
IHB	- Ivanpah Hydrographic Basin
IVFS	- Ivanpah Valley Flow System
IVN	- Ivanpah Valley North
IVS	- Ivanpah Valley South
JLV	- Jean Lake Valley
K	- Hydraulic conductivity
km	- Kilometer
LVIS	- Las Vegas Isotope Studies
LVVWD	- Las Vegas Valley Water District
m	- Meter
NDWR	- Nevada Department of Water Resources
SNWA	- Southern Nevada Water Authority
SC	- Specific capacity
SRM	- Sierra Ready Mix Well

SRP	- Service Rock Products Well
T	- Transmissivity

CHAPTER ONE - INTRODUCTION

Ivanpah Valley (Figure 1.), located between Las Vegas, Nevada and Cima, California, is a north-south trending valley bounded by geologic structure typical of basin and range topography (Hewett, 1956). Located in the Mojave Desert, the groundwater and occasional isolated springs of Ivanpah Valley are an important natural resource for the many uses of mining, commercial, and industrial activities occurring within the valley. This research was conducted to examine the hypotheses that there was potentially hydrogeologically isolated sub-basin bounded by geologic structures in the northeastern area of Ivanpah Valley, and determine if the area would be suitable for artificial recharge of groundwater within the confines of the Nevada portion of the valley.

Artificial recharge of groundwater has been shown to supplement water supply throughout the desert southwest (Pyne, 2007). The practice is to add groundwater to an existing aquifer with available storage capacity for future use. Groundwater can be recharged in a variety of methods, but the most common are artificial storage and recovery (ASR) utilizing injection and recovery wells (Pyne, 2007), and surface percolation impoundments where water percolates through the vadose zone, overcoming the differences in hydraulic potential and reaching the water table via gravity (Stephens, 1995). The parameters governing successful artificial recharge operations (discussed further in Chapter 4) center on the native aquifer characteristics and the engineering and operational methods utilized in the recharge and recovery of the stored water(s).

Hypotheses

The hypotheses tested in this research were:

1) The Ivanpah and Jean Lake Valleys near the McCullough Mountains and the Lucy Gray Mountains are composed of coarse grained alluvial aquifer(s) which would support artificial groundwater recharge and recovery operations.

2) The northeastern portion of Ivanpah Valley, including Jean Lake Valley, is partially isolated from the major portion of Ivanpah Valley groundwater flow and is a distinct sub-basin. The sub-basin has its own recharge regime, and structurally controlled preferential groundwater flow pathways.

The research investigated the hydrogeologic characteristics of the study area to address the hypotheses and determine if northeast Ivanpah Valley may be a viable location for artificial recharge. The basic criteria for successful artificial recharge include: acceptable native water quality, high permeability and porosity, structurally impeded groundwater flow, and proximity to excess water. Native water quality data was analyzed and interpreted for acceptable water quality parameters needed for artificial recharge and storage. Stable and radiometric isotopes were utilized to determine the natural groundwater recharge and groundwater travel time. Field mapping of geologic structure occurred to determine if possible impediments to groundwater flow existed. General aquifer parameters based upon previous data was estimated to define if the aquifer would

support artificial recharge operations. And natural precipitation estimates were compiled to determine if excess precipitation runoff was available for groundwater recharge.

Importance of Research

The importance of this research centers on the water supply demands of Southern Nevada, which depends on the Colorado River for 90% of its water needs. If no future water resource development occurs, Southern Nevada will exceed its current supply by 2020 (SNWA, 2009). Therefore, the identification of a structurally isolated sub-basin independent of the Ivanpah Valley Flow System (IVFS) (CADWR, 2003), could be a favorable area for artificial groundwater recharge to enhance the local water supply within Ivanpah Valley and also potentially serve as groundwater storage area for Southern Nevada. Given the proximity of Ivanpah Valley in relation to the heavily populated Las Vegas Valley, and the rapid industrial development occurring within Ivanpah Valley, an artificial recharge operation in a structurally isolated groundwater storage basin in this area could help to serve the water needs of the Southern Nevada region.

CHAPTER TWO – PROJECT AREA CHARACTERISTICS

Project Area Physiography

The project area is located in southern Nevada in Clark County (Figure 1). Ivanpah Valley is a shared watershed, with a majority of the basin area and groundwater recharge occurring in California. Ivanpah Valley is a north – south trending valley approximately 56 kilometers (35 miles) in length and stretches across the California - Nevada state line.

The study area encompasses northeast Ivanpah Valley and Jean Lake Valley. The closest towns to the study area are Jean, Nevada, along the northern boundary of the study area (Figure 1) approximately 6 miles (9.66 kilometers) to the southwest of Jean Lake Valley; and Primm, Nevada, which is along the western boundary of the study area (Figure 1). The borders of the study area were chosen based upon the hydrographic and structural features of Ivanpah Valley. The study area is approximately 225 square miles (583 square kilometers) in size. The area ranges in elevation from 2750 feet (838 meters) above mean sea level (amsl) at the lowest point of the valley floor at Jean Dry Lake to 7026 feet (2142 meters) amsl in the McCullough Mountains. Ivanpah and Jean Lake Valleys are topographically closed basins within which surface-water drainage evaporates on either the Ivanpah Lake, Roach Lake, or Jean Lake playas.

Climate and Vegetation

The climate of northeastern Ivanpah Valley is typical of the transition zone between southern Basin and Range and the Mojave Desert with hot, dry summers and mild winters (Turner, et al., 1984). The area receives over 75% of annual precipitation during the winter and spring months, with the remaining 25% occurring as summer monsoonal moisture (precipitation is discussed further in this chapter) (CADWR, 2003). The vegetation of the study area ranges from creosote scrub below 4000 feet (1219 meters) to Pinyon Pine – Juniper woodland above 6000 feet (1829 meters) (Turner, et al., 1984).

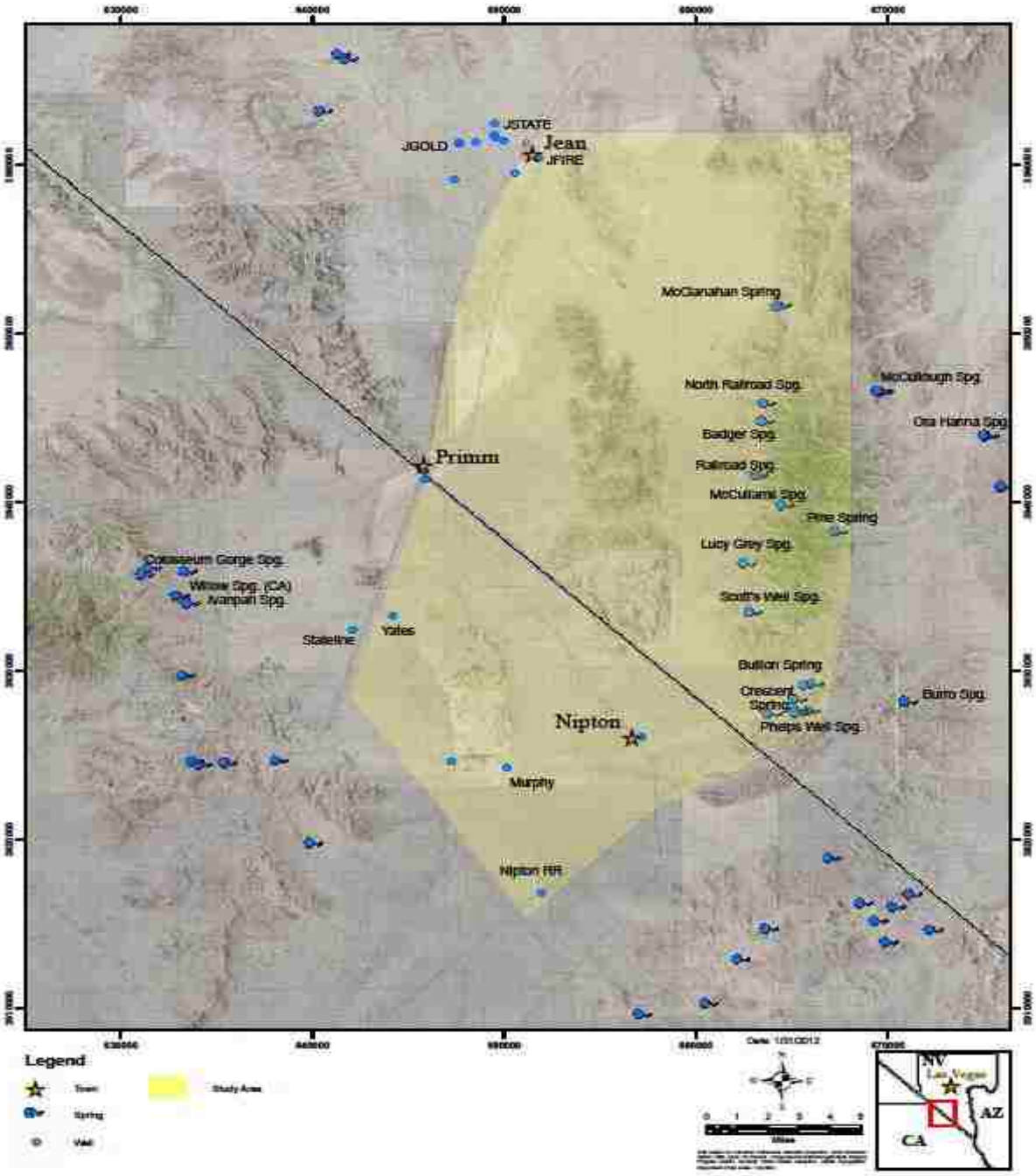

Figure 1. Map showing the study area (yellow shading) in relation to geographic features in Ivanpah Valley. The town of Primm, Nevada, lies on the California – Nevada state line. The town of Jean, Nevada is located on the northwestern corner of the study area. Springs and wells are shown as blue symbols.

Geology and Aquifer Composition

Ivanpah Valley is within the geologically complex Basin and Range Province of the Mojave Desert, exhibiting northwest trending structural features with horst and graben topography bounded by normal faults (Hewett, 1956).

A number of authors have investigated the surficial geology of Ivanpah Valley [e.g. Hewett (1956), Plume (1996), Harrill and Prudic (1998), House et al. (2006a, 2006b and 2006c)]. In summary, consolidated rocks exposed at the surface are composed of carbonate, intrusive, and extrusive origin, while unconsolidated deposits are of alluvial, pluvial, colluvial, or eolian origin. Figure 2 – Geology shows the basic surface exposures of the consolidated rocks and unconsolidated deposits within the study area based upon these previous studies.

Consolidated Units

The consolidated units of Ivanpah Valley range in age from Precambrian to Tertiary (Hewett, 1956; Plume, 1996; Harrill and Prudic, 1998; and House et al., 2006a, 2006b, 2006c). The carbonate outcrops are of Precambrian and Paleozoic age within the Spring Mountains, Bird Spring Range, and Sheep Mountains on the northwestern and northeastern borders of Ivanpah Valley. The intrusive rocks are primarily pre-Cambrian and Mesozoic aged granitic rocks found in the McCullough Range, Lucy Gray Mountains, New York Mountains, Clark Mountain Range, and Ivanpah Mountains on the southeastern and southwestern borders of Ivanpah Valley (Hewett, 1956; Plume, 1996; Harrill and Prudic, 1998; and House et al., 2006a, 2006b, 2006c. The

consolidated rocks are underlain by a basement of Proterozoic aged silicate metamorphic rocks commonly found throughout the eastern Mojave (Miller et al., 1991).

The consolidated rocks specific to the study area are mostly Proterozoic aged granitics found within the McCullough Range and Lucy Gray Mountains, extrusive rocks of primarily basaltic composition of Tertiary and Quaternary age occurring within the northern McCullough Range on the eastern border of Jean Lake Valley and carbonate rocks found in the Sheep Range near the town of Jean, Nevada (Hewitt, 1956).

The hydraulic properties of the consolidated rocks generally vary greatly depending upon the rock type (Plume, 1996; Harrill and Prudic, 1998). The carbonate rocks in the area are most permeable of the rock types, with pore space formed by dissolution, and fault and fracture zones created by faulting, generally increasing permeability. The granitic and basaltic rocks are poorly permeable at large scales. While these rocks are fractured in the study area, the fracture connectivity and small fracture size can limit the intrusive and extrusive rocks from transmitting groundwater via underflow (Harrill and Prudic, 1998).

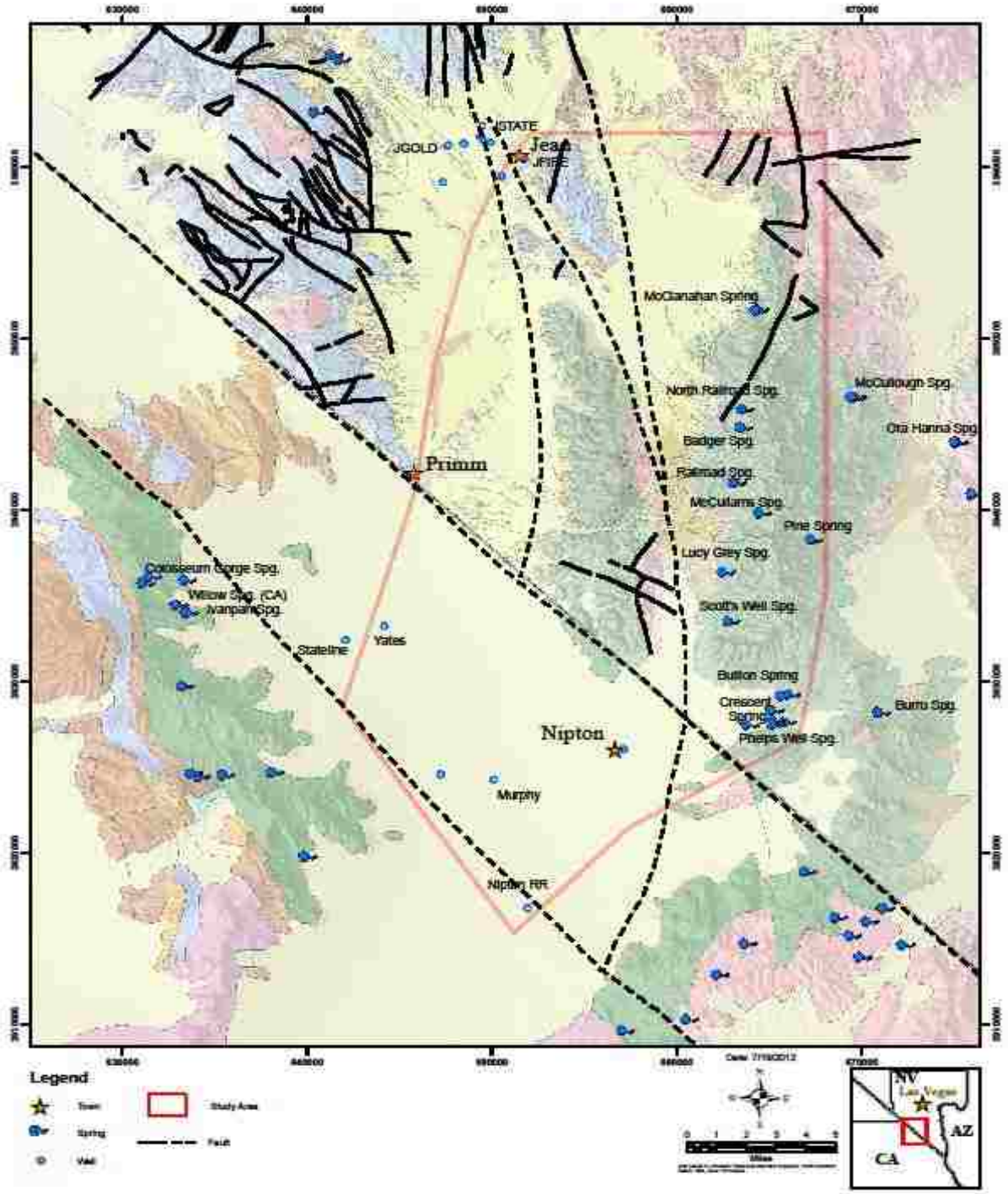

Figure 2. Map showing the study area (red outline) in relation to major geologic features of Ivanpah Valley. Geologic units shown are carbonates (blue color), igneous rocks (green color), metamorphic rock units (brown color) and volcanic rocks (pink color).

Unconsolidated Deposits

The unconsolidated deposits of northeastern Ivanpah Valley and Jean Lake Valley is known mainly through extrapolation of the surrounding exposed geologic units and drillers logs. The most detailed evaluation of northern Ivanpah Valley was conducted by Molycorp (2008), which indicated the valley to be filled with sediments of clays, silts, sands and gravels from alluvial deposition. Coarser alluvial fan sediments are generally found closer to the McCullough and Lucy Grey Mountains and tend to interfinger with the fine grained deposits near the playas of Roach Dry Lake and Jean Dry Lake (House et al., 2006a, 2006b). The unconsolidated deposits primarily consist of Pliocene to Holocene aged alluvial and playa deposits (Hewett, 1956; Plume, 1996; House, 2006). The older alluvium consists of alluvial fan deposits of Pliocene and early Pleistocene age is composed of gravels, sands, and silts with minor boulders and clay. The older alluvium underlies the valley-floor of the study area within both northeastern Ivanpah Valley and Jean Lake Valley, is generally found below the regional groundwater table, and is known to produce acceptable yields for production wells (West Yost, 2014).

The younger alluvium consists of late Pleistocene and Holocene aged alluvial-fan deposits. The younger alluvium is composed of gravels and sands with minor amounts of silt and clay, generally found above the regional groundwater table, and occasionally contains perched groundwater within fine grained deposits near the toe of the fan(s). The playa deposits are composed of Holocene aged pluvial deposits of fine sands, silts, and clays. The playa deposits are above the regional groundwater table, and only temporally and spatially variable perched groundwater occurs within the playas.

Structural Features

Extensive faulting occurs throughout Ivanpah Valley (Hewett, 1956) consisting of thrusts and normal faults (Figure 2). According to Hewett (1956), thrust faulting occurred during the Mesozoic era, resulting in the deformation of the carbonate and Precambrian crystalline rocks. Significant normal faulting occurred during Tertiary crustal extension, producing deformation of the consolidated rocks and also forming the downdropped structural basins which were then filled with the unconsolidated deposits. The major thrust faults within Ivanpah Valley are the Mesquite, Keystone, and Contact Faults (Hewett, 1956). All of these thrust faults are outside the study area.

The major normal faults in the study area are the Stateline, Ivanpah, Roach, and McCullough faults (Hewett, 1956). The Stateline fault has the hanging wall on its southwest side, the Ivanpah Fault block is down-dropped to the northeast, the McCullough fault block is down-dropped to the west, and the Roach Fault is also down-dropped on its west side. These displacements produce a northwestward trending structural basin which forms Ivanpah Valley. This trough deepens toward the center of Ivanpah Valley (Langenheim et al., 2009). The trough correspondingly is filled with unconsolidated deposits that are several hundred to over a thousand feet in thickness (Langenheim et. al., 2009).

Hydrogeology

Groundwater movement in the alluvial aquifer(s) is from south to north, which is classified as the Ivanpah Valley Flow System (IVFS) (CADWR, 2003). Groundwater flow in the IVFS originates in California in the Mojave National Preserve via precipitation in the New York Mountains, Cima Dome, Clark Mountains (Mountain Pass), and the Mescal Range, and flows northward through Ivanpah Valley crossing the geographic boundary between California and Nevada, eventually terminating in the southern Las Vegas Valley.

The study area for this research, located in northeastern Ivanpah Valley (Figure 1), is designated by the Nevada State Engineer to be composed the hydrographic areas of Jean Lake Valley (Hydrographic Area 165), Ivanpah Valley North (HA 164A), and Ivanpah Valley South (HA 164B) (Attachment A). Localized groundwater recharge within the study area occurs from precipitation in the McCullough and Lucy Grey Mountains on the eastern side of Ivanpah and Jean Lake valleys (Glancy, 1968). Precipitation which falls at the lower elevations along the valley floor appears to be consumed mostly by evapotranspiration (Molycorp, 2008). At higher elevations, high precipitation events can produce stream flow, and also deeper infiltration into the mountain block via fracture flow (Molycorp, 2008). Runoff contributes to groundwater recharge by infiltration on the alluvial fans along the mountain fronts (Molycorp, 2008). Additionally, infiltration through the mountain block via fractured bedrock in the McCullough Mountains produces recharge in the form of springs and also groundwater flow into the alluvial deposits (Moore, 1968). The geomorphology of the study area within Ivanpah Valley is influenced by the

granitic terrains which demonstrate dense stream-channel networks, in which streambed infiltration tends to be the dominant recharge.

The localized groundwater recharge in the study area flows northward and southward towards the Roach, Ivanpah and Jean dry lakes before being partially captured by the regional Ivanpah Valley Flow System (CADWR, 2003). The geologic structural impediments in the form of bedrock and faults influence the groundwater pathways in these north and south directions, impeding east-west groundwater flow (Rojstaczer, 1987). Granitic and basaltic rock within the McCullough Range and New York Mountains prevent groundwater flow between Ivanpah Valley and the adjacent Piute Valley to the east and Lanfair Valley to the south (Langenheim et al., 2009). The northwest trending structures allow groundwater to flow continuously along the IVFS through Ivanpah Valley eventually terminating in southern Las Vegas Valley (Langenheim et al., 2009). The current inflow contribution from Ivanpah Valley to Las Vegas Valley is estimated to be 1,500 afy (185 hectare meter per year) (Molycorp, 2008 after Glancy, 1968).

The alluvial fill is the primary aquifer in the northern and southern areas of the valley, including Jean Lake Valley. The maximum thickness of the alluvial fill exceeds 750 feet (228 meters) (Glancy, 1968). The depth-to-water varies throughout Ivanpah Valley, but is generally shallower near the valley floor and higher near the mountains. The measured depth-to-water ranges from 77 feet (23 meters) to 750 feet (228 meters) below ground surface in Ivanpah Valley (Acheampong, 2003).

The potentiometric surface of the study varies from 2969 feet (902.6 meters) amsl to 2135 feet (649 meters) amsl in the study area. Table 1 below shows a statistical sampling of recorded static water levels from wells located in the proposed sub-basin and wells located within the IVFS.

The SRM and SRP wells (located in the northern portion of the proposed sub-basin) are adjacent to the McCullough Fault have water levels approximately 100 to 200 feet (30 to 60 meters) lower than wells to the west of the McCullough and Roach Fault junction, outside of the proposed sub-basin.

Table 1. Water levels at selected wells in IVFS and the proposed sub-basin. Water levels found in the SRM and SRP wells, east of the McCullough Fault, are significantly lower than the water levels found in wells JGold, JState, and J-7 located west of the McCullough Fault.

IVFS Wells - Water Level Data					
Well	**Date**	**WL (ft)**	**Status**	**Elevation (Ft)**	**AMSL (ft)**
NIPR&R	13-Jun-12	371.42	Static	3341	2969.58
STATELINE	19-Mar-12	219.90	Static	2662	2442.10
YATES WELL	13-Jun-12	95.28	Static	2734	2638.72
CALLAHAN	6-Mar-12	230.67	Static	2699	2468.33
JSTATE	6-Mar-12	495.44	Static	3028	2532.56
JGOLD	26-Jan-12	585.15	Static	3076	2490.85
J-7	2-Aug-12	367.23	Static	2851	2483.77
Sub-Basin Wells – Water Level Data					
Well	**Date**	**WL (ft)**	**Status**	**Elevation (ft)**	**AMSL (ft)**
SRM	2-Aug-12	640.41	Static	3026	2385.59
SRP	2-Aug-12	557.43	Static	2693	2135.57

Groundwater Recharge and Use

Ivanpah Valley is generally divided into two basins based on hydrographic boundaries and the California - Nevada state line (Figure 3). Ivanpah Valley North (IVN) generally exists north of the California – Nevada state line, and Ivanpah Valley South (IVS) is south of the state line, however; the boundary of IVS also includes the hydrographic boundary established by the Nevada Department of Water Resources (Attachment A). On the Nevada side, the area is divided into three hydrographic areas: Ivanpah Valley North (HA 164a), Ivanpah Valley South (HA 164b), and Jean Lake Valley (HA 165) (Attachment A). The previous studies by Molycorp (2008) and Langenheim et al. 2009, consider IVN, IVS, and JLV to be within the larger IVFS.

For the purposes of investigating the existence of a sub-basin whose boundaries are based upon geologic structure north of the California - Nevada state line, the water use and recharge estimates are based upon those reported by the NDWR.

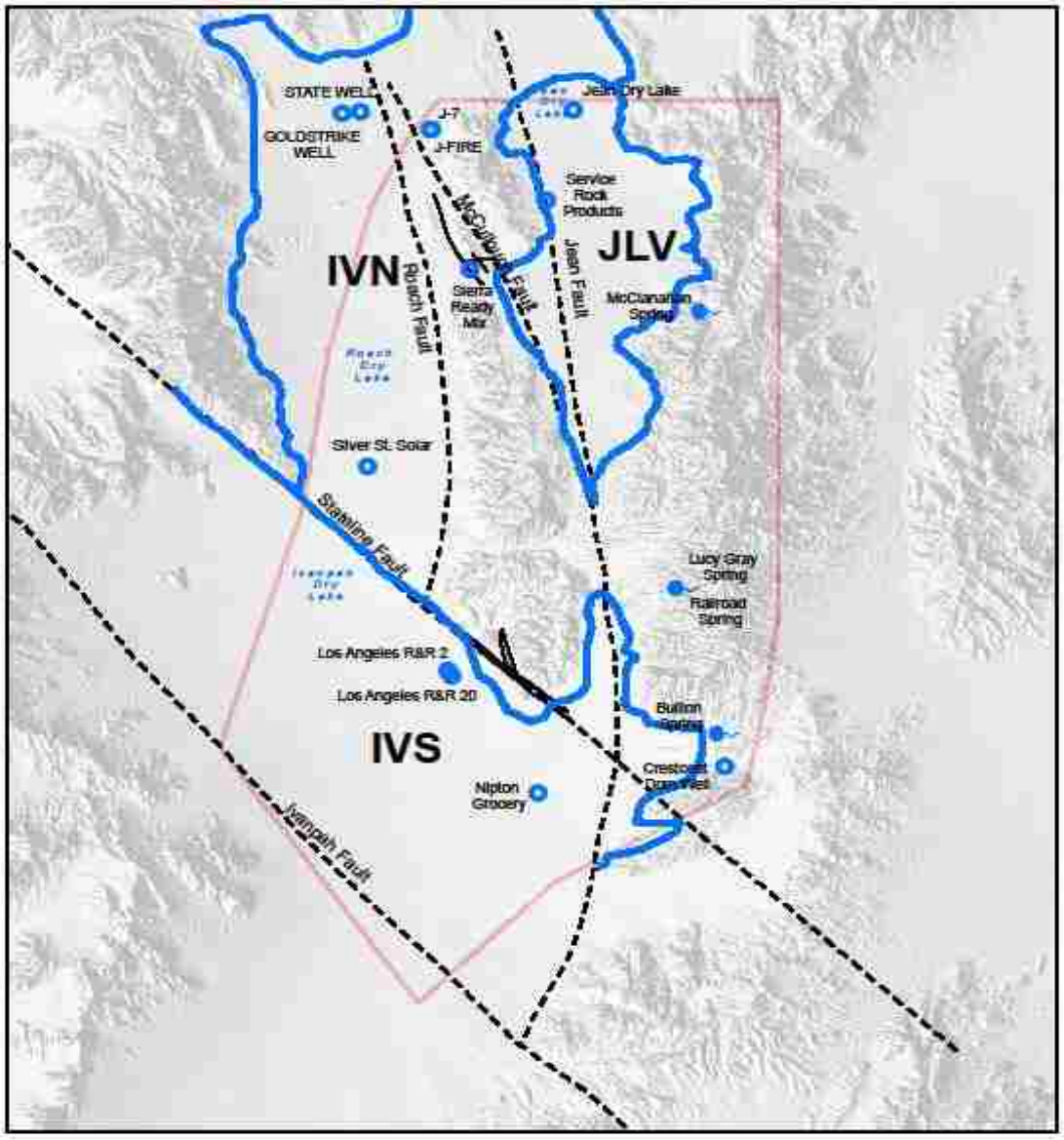
STATE WELL
GOLDSTRIKE WELL
J-7
J-FIRE
Jean Dry Lake
Service Rock Products
McCullough Fault
Jean Fault
IVN
JLV
Sierra Ready Mix
McClanahan Spring
Roach Fault
Roach Dry Lake
Silver St. Solar
Stateline Fault
Ivanpah Dry Lake
Lucy Gray Spring
Railroad Spring
Los Angeles R&R 2
Los Angeles R&R 20
Button Springs
IVS
Nipton Grocery
Ivanpah Fault
Legend
Study Area
Fault
Sample Locations
and
SubBasin Boundaries
NV
AZ
CA

Figure 3. Basin boundaries of Ivanpah Valley showing Ivanpah Valley North (IVN), Ivanpah Valley South (IVS), and Jean Lake Valley (JLV), all of which are considered to be included in the Ivanpah Valley Flow System (IVFS). The NDWR Hydrographic Areas of Nevada within the study area are shown on Attachment A.

Water Balance

The higher elevation McCullough Mountains receive approximately 8-12 inches (20 to 30 cm) of precipitation annually, while the lower valley floor of Jean lake Valley and Ivanpah Valley receive less than 4 inches (10 cm) of precipitation annually (Molycorp, 2008).

The streams and washes of northeastern Ivanpah Valley are ephemeral, carrying water from the higher elevations for only short periods of time during storm runoff or brief spring snow melts. These stream channels are generally coarse grained and water infiltrates quickly into the alluvial sediments. The total runoff acreage was estimated by Glancy (1968) at 74,300 acres (30,081 hectares) of runoff area with approximately 1,200 acre-feet (148 hectare meter) of water for IVN, leading to approximately 685 afy (85 hectare meter per year) of annual groundwater recharge. Jean Lake Valley accounts for 27,800 acres (11,231 hectares) in runoff area providing an average annual runoff of 250 acre feet (30.8 hectare meter), with an estimated 88 afy (10.8 hectare meter per year) of total infiltration recharge (Glancy, 1968). Presently, the water balance for northeastern Ivanpah Valley appears to exceed natural recharge; however, the estimated recharge in Jean Lake Valley exceeds pumpage by 50 afy (6.2 hectare meter per year), leaving Jean Lake Valley with a net surplus of water (Molycorp, 2008).

According to the Nevada Department of Water Resources (NDWR 2013a; NDWR 2013b) the estimated water use for the hydrographic areas (HA) in Ivanpah Valley including Jean Lake Valley (excluding California) is the following:

Jean Lake Valley (165) = 50.22 afy (6.2 hectare meter per year)

Ivanpah Valley North (164a) = 2,948.19 afy (363.5 hectare meter per year)

Ivanpah Valley South (164b) = 1,837.99 afy (226.6 hectare meter per year)

Total potential withdrawal = 4,836.4 afy (596.3 hectare meter per year)

Additionally, recharge from Las Vegas Valley Water District (LVVWD) infiltration basins in Jean, Nevada account for a calculated annual recharge of 519.31 afy (64 hectare meter per year) (Acheampong, 2003). The estimated underflow from IVS to IVN across the Ivanpah and Stateline faults is approximately 800 afy (98.6 hectare meter per year) (Molycorp, 2008).

The total available perennial recharge of IVN, IVS and JLV is therefore 3374.3 afy (416 hectare meter per year). The overall groundwater usage in Ivanpah Valley is approximately 4,836.4 afy (596.3 hectare meter per year) in permitted water rights, exceeding the natural groundwater supply by 1,462.1 afy (180.3 hectare meter per year).

CHAPTER THREE – RESEARCH PLAN AND METHODOLOGY

Sample Selection Criteria

Samples were collected within the study area in order to estimate the native water quality and the age of groundwater(s) in the proposed sub-basin and the remainder of Ivanpah Valley. Sample sites (consisting of springs and wells) were chosen based on access, historical geochemical information (if any), their relationship to proposed groundwater flow pathways, structural features, and possible aquifer infiltration and recharge. Spring selection was also based upon if the presence of enough fresh water flow would allow sampling. The samples were collected to fill gaps within existing data from previous studies. Several historical water quality sample locations were incorporated into the research (Mark Group 1988, Molycorp 2008, LVVWD 2012) to provide data completeness and better understand the groundwater geochemistry of the study area; however, the historical analyses occasionally demonstrated variability in the chemical constituent datasets. Additionally, stable isotope analysis for δD and $\delta^{18}O$ and Tritium were collected from selected sites based upon the statistical analysis and spatial variability of the cation and anion geochemical results. Previous studies (Molycorp 2008, Glancy 1968, The Mark Group, 1988), have determined the playa deposits in IVN play a major role influencing groundwater geochemistry. The sample locations used in this study were selected to be away from the playas (except Jean Lake) so as to minimize their geochemical influence upon the groundwater samples.

Sampling Methodology

Groundwater collected from springs and wells was measured for field parameters of temperature, pH, and electrical conductivity during sampling. These samples were collected for laboratory analysis of major anions and cations, stable isotope analysis of oxygen and hydrogen, and Tritium analysis. A total of nine samples were taken during this research. The sample location are shown in Figure 4 and discussed further in Chapter Three.

The sampling methodology consisted of collecting water directly from fresh flowing springs and purging all wells prior to sample collection to ensure samples were collected from fresh water. Three well volumes were purged using the volumetric calculation of the water standing inside the well and then measuring the discharge in gallons per minute (gpm). Field parameters were recorded during sample collection using a Hach 160NP meter measuring temperature, pH, and electrical conductivity data. The Hach 160NP meter is temperature compensating. The meter was calibrated daily before use with pH standards of pH 4.00, pH 7.00 and pH 10.00 using a three point calibration, and 500 μs/cm and 1000 μs/cm conductivity standards supplied by the SNWA water quality lab.

Analysis of major ions, stable isotopes of hydrogen and oxygen, and Tritium was needed to aid in distinguishing the source and movement of subsurface water. Samples for major cations and anions were collected in clean styrene one pint bottles. The δD-$\delta^{18}O$ stable isotope samples were collected with no head space in 20 ml borosilicate vials with sealed caps to prevent evaporation. Tritium samples were collected in 1 liter clean styrene bottles with sealed caps to prevent evaporation. Samples were placed in iced coolers while in the field and subsequently

refrigerated prior to transport to the laboratory per analytical protocols. Delivery was within analytical hold times, and chain-of-custody protocols of each laboratory were followed.

Analyses were performed at the certified laboratory at the Southern Nevada Water System (SNWS), Las Vegas Isotope Studies Laboratory (LVIS) and Brigham Young University (BYU) Isotope Laboratory in Provo, Utah. Cations were analyzed using EPA 200.8 method at SNWS. Analyses of major cations consisted of sodium (Na^{+}), potassium (K^{+}), calcium (Ca^{2+}), and magnesium (Mg^{2+}); major anions (chloride (Cl^{-}), nitrate (NO_3^{-}), and sulfate (SO_4^{2-}); alkalinity as bicarbonate (HCO_3^{2-}); silica (SiO_2); and total dissolved solids.

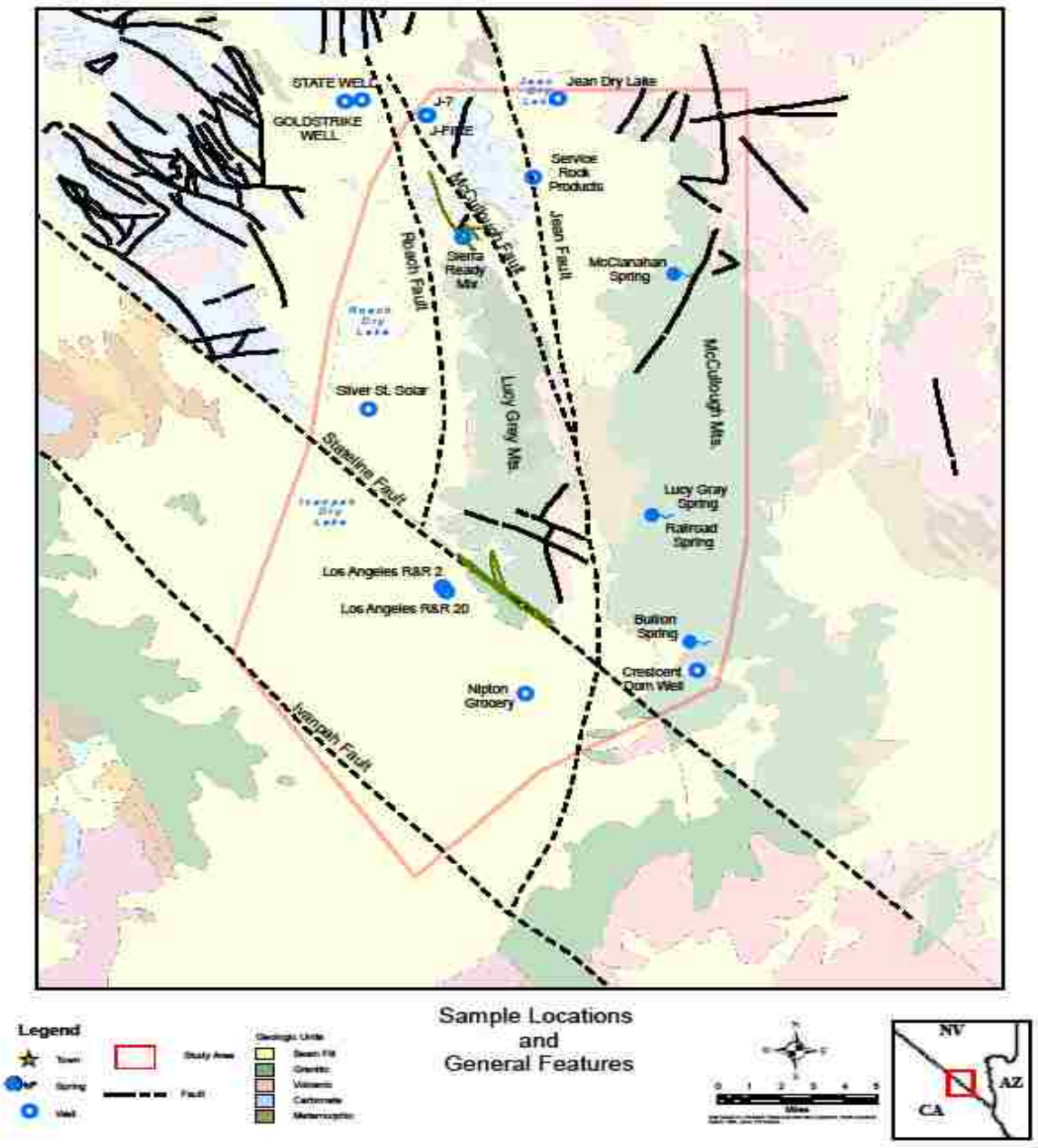

Figure 4. Map showing the study area (red outline) in relation to Ivanpah Valley. Basic geology of major faults, consolidated rocks and alluvium are included. Springs and wells used in this study are shown as blue symbols.

Statistical Analysis and Isotope Calibration

Basic statistical methods were employed to evaluate the overall value and variability of all water quality parameters. Arithmetic mean, standard deviation, and skewedness for each geochemical constituent were calculated for both the data collected for this research and also the historical data sets for each sample location.

Stable isotopes are used to examine groundwater recharge and transport within a watershed by examining the ratios of $^{2}H/^{1}H$ (Deuterium) and $^{18}O/^{16}O$ ($\delta^{18}O$), and their distribution in relation to the local meteoric waterline. This allows insight into the environmental processes impacting the fate and transport of groundwater. Rayleigh Distillation enriches the heavier isotopes of precipitation and can be used to determine climatic and seasonal effects in the Great Basin (Lachniet, 2014).

Stable isotopes of oxygen and hydrogen were calibrated using laboratory calibration standards, statistical analysis of both the calibration standard and samples using standard deviation, and a two point linear calibration of the results. Results were compared to the global and a local meteoric water line.

The samples were analyzed at the BYU Isotope Laboratory for isotopic ratios of Tritium hydrogen (^{3}H), as mentioned in the previous chapter. The analysis was performed on the light isotope ratio mass spectrometer (IRMS) at BYU. The IRMS measured the relative abundance of isotopes from a particular sample.

BYU Isotope Laboratory performed analysis on a total of nine samples that were identified during the field investigation as being most spatially representative to determine groundwater pathways and travel time.

Thermonuclear Tritium is a remnant of above ground nuclear testing from the 1950s to the late 1970s and is used in groundwater studies for age dating. The radioisotope ^{3}H is measured using the ratio between $^{3}H/^{1}H$ using the equation (Clark, 2012):

$$^{3}H/^{1}H = 1/10^{18} = 1 \text{ Tritium Unit (TU)}$$

Tritium has a half-life of 12.32 years (Clark, 2012) and readily has entered the hydrologic cycle. Tritium can be used for age dating techniques by measuring the amount of decay. During the "Bomb Peak" in 1963, Tritium measured in North American groundwaters reached over 1,000 TU (Clark, 2012). Modern day Tritium ranges between 0.1 to 7.0 TU.

Tritium results were calculated using methods described by Clark, (2012) at the BYU Isotope Laboratory and shown in Chapter 4.

Quality Assurance

Calculation of the cation to anion ratios involved using the sum of the milliequivalents for anions divided by the sum of the milliequivalents for the cations (Equation 1, Piper, 1944). The calculation of the milliequivelents occurs by dividing the concentration by the atomic mass of the ion, and multiplying the result by the ionic charge (Dano, 2010). By electroneutrality, anion charge and cation charge will balance, resulting in a cation to anion ratio of 1.0 in the absence of analytical errors.

$$\left(\sum_{\text{Anions}} \frac{NO_3^-}{62.01} + \frac{Cl^-}{35.45} + \frac{2(SO_4^{2-})}{96.07} + \frac{(CaCO_3)*1.22}{61.018}\right) / \left(\sum_{\text{Cations}} \frac{Na^+}{62.01} + \frac{K^+}{39.1} + \frac{2*(Ca^{2+})}{40.08} + \frac{2(Mg^{2+})}{24.31}\right) \quad \textbf{(1)}$$

Piper Diagrams

Piper diagrams are used to graphically represent the variables associated with major cation and anion data and aid in the determination of similarities and differences in water samples (Piper, 1944). A Piper diagram is composed of two triangles and a rhombus. The triangles represent milliequivalent percentages of three sets of components totaling 100%. The components are labeled on the corners of the triangle, with one triangle representing cations on one corner, Na +K, components on another, and SO_4^{2-}+ Cl^- and HCO_3^- on another. The Piper diagrams shown in Figures 6 and 7 were plotted using using the software product Microsoft Office Excel 2013.

Structural Analysis

Structural mapping utilizing 1:24,000 base maps and field techniques described in Compton (1985) were completed to determine the locations of the McCullough, Roach, and Stateline faults within the study area (Figures 3, 4). The investigation of these faults was needed to determine if transverse groundwater flow may be impeded by the faults from the recharge areas in the McCullough Mountains to the lower elevations in Ivanpah Valley. Faults and other structures are generally known to affect groundwater flow (Bedrosian, et. al., 2013). Normal faults tend to impede transverse groundwater flow, but these faults can also act as conduits for longitudinal groundwater flow (Rojstaczer, 1987). If surface expression of the faults was

evidenced, it could further support the hypothesis of an isolated sub-basin within the Ivanpah groundwater flow system.

Infiltration and Recharge

Estimating the amount of infiltration of precipitation through coarse grained fan material in dry washes was initially proposed for this research. The test method used to provide a field measurement of the rate of water infiltration into the soils was to measure the change in height of an ephemeral stream flow above the stream channel multiplied by the length of the flow and the width of the channel (USGS 2014), subtracting the normal estimation for evapotranspiration using the Maxey-Eakin (1949) method during the wetting event. Remote streambed In-Situ LEVEL TROLL 500^{TM} data loggers were deployed in four alluvial drainage channels to measure the height of water in the channels. Two data loggers were deployed in the Jean Lake Valley hydrographic drainage, and two in the southern Ivanpah hydrographic drainage, in June of 2013. Other test methods were found to be either inefficient in the collection of infiltration data or were not approved for use by the Bureau of Land Management (i.e. Double Ring Infiltrometer).

Map Creation

Geographical Information System (GIS) software are typically used to spatially represent datasets for the purpose of generating maps and making spatial comparisons of data. The product ArcMap®, version 10.0 from ESRI was used for all maps generated for this research. The base coordinate system used is the North American datum from 1983 (NAD 83). ArcMap® 10.0 was

the primary tool used for producing maps used in this analysis. The maps spatially integrated Ivanpah Valley physiography, geologic mapping, water sample locations, and geochemical results.

CHAPTER FOUR – RESULTS

Field Mapping of Structure

The McCullough fault in the area of Sierra Ready Mix (SRM) sample location, 1 mile southeast of Jean, Nevada, shows little surface expression due to overlying alluvium along the projected fault pathway (Figure 4). However, structural data were obtainable via the carbonate outcrops adjacent to Sheep Mountain from field mapping using standard strike and dip data collection (Figure 5). These outcrops sandwich the assumed projection of the McCullough fault. The results of the structural analysis collected for this study found opposing attitudes of the outcrops. Outcrops north of the fault displayed northward strike averaging 315 degrees and east 34 degrees. Outcrops to the south of the fault zone displayed a western strike of 245 degrees with shallow dips to the north at 20 degrees. Additionally, a fresh mining excavation was mapped within the fault zone and a smaller scale fault was found striking 325 degrees northwest, dipping 50 degrees southwest (Figure 6). The location and generalized strike of the McCullough fault determined during field mapping was then projected southward to fault locations east of the Lucy Gray Mountains previously mapped by Schimdt and McMackin (2006). The fault location found from structural mapping for this research, and the inferred projections of the fault by Schimdt and McMackin (2006), are within the flow boundaries of the Molycorp (2008) basin conceptual model, further supporting the findings of this research.

The Stateline fault within the area of the Lucy Gray Mountains was also mapped along the projected strike. The surface expression of the fault is clearly visible; however, the fault cuts through consolidated rocks of mylonitic Proterozoic basement rock which is extensively folded,

and reliable strike and dip data of bedding could not be collected. The directional strike of the fault was noted and mapped along the surficial expression within the Lucy Grey Mountains. The findings of the field mapping and fault strike data supported the validity of the interpretation of a northwest striking fault with a down to the northeast hanging wall orientation (Figure 7), and validated the projections of Stateline Fault by Schimdt and McMackin (2006).

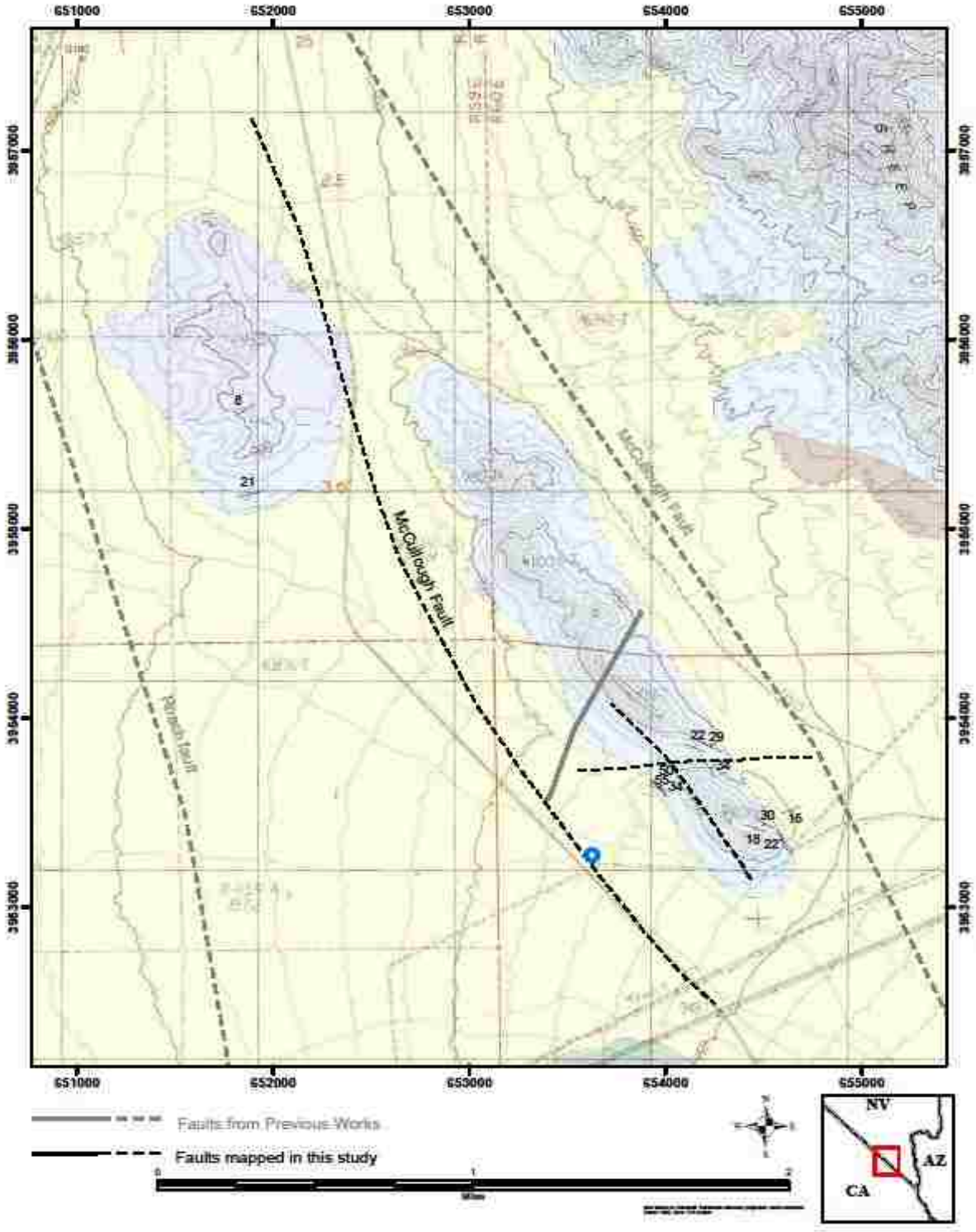

Figure 5. Field map of the McCullough and Roach Fault junction southeast of the town of Jean, Nevada. The faults are buried under alluvial deposits and were inferred by Schmidt and McMackin (2006). Structural analysis of

bedding within carbonate outcrops adjacent to the faults further refined the inferred projections. The strike and dip of the outcrops found opposing attitudes across the inferred faults.

Figure 6. Photo of faulting in a mining excavation near the inferred location of the McCullough Fault, southeast of the town of Jean, Nevada (water bottle in lower left-hand corner for scale). The fault is striking 325 degrees to the northwest, and dipping 50 degrees to the southwest.

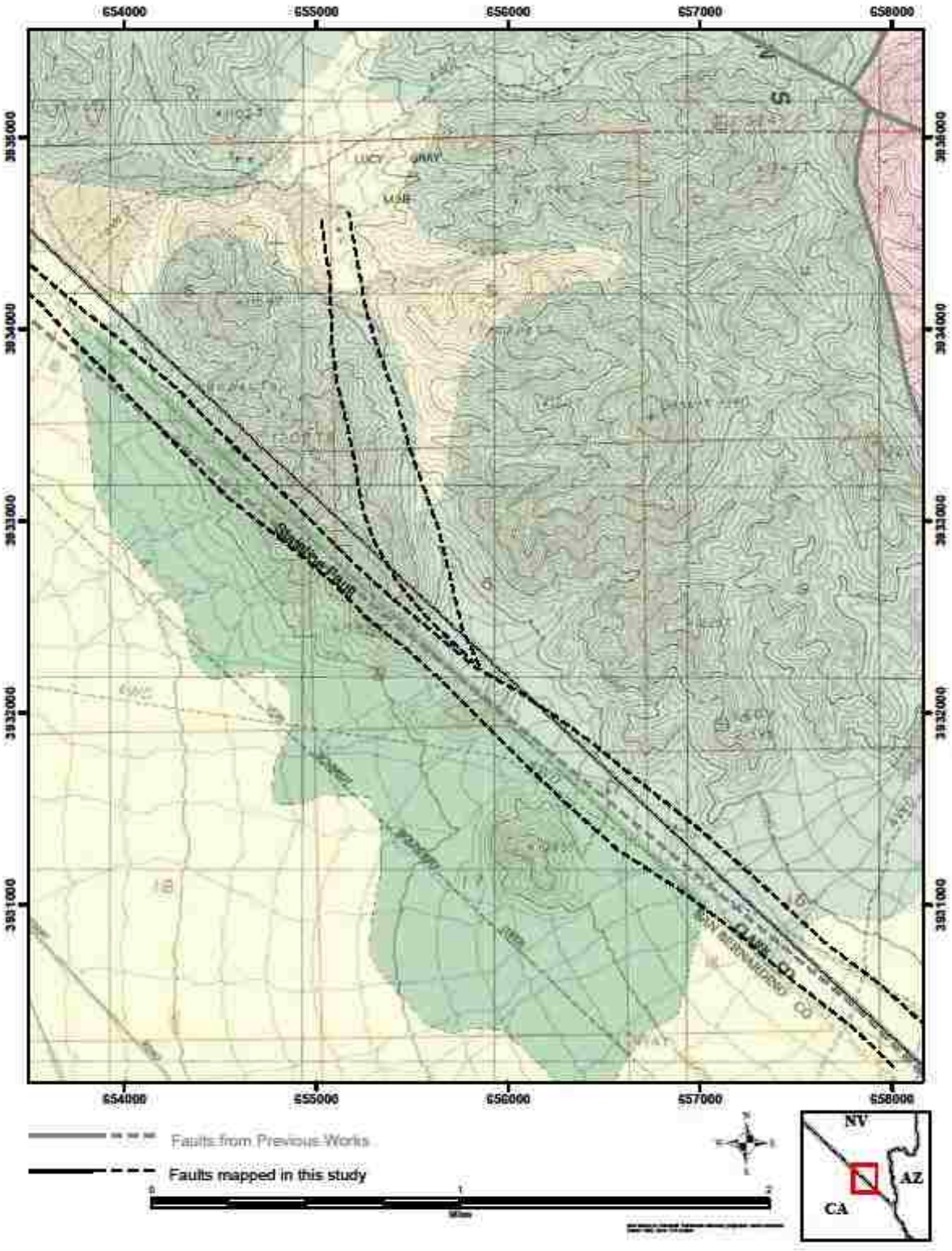
654000
655000
656000
657000
658000
3836000
3834000
3832000
3830000
3828000
Faults from Previous Works
Faults mapped in this study
NV
AZ
CA

Figure 7. Field map of the Stateline Fault near the California – Nevada border in the Lucy Grey Mountains. The fault strike was clearly visible in the Proterozoic aged mylonitic rock, but due to the extensive folding, bedding could not be reliably determined.

Study Area Aquifer Characterization

Lithologic information for seven wells within the study area was obtained from the Nevada State Engineer. The lithologic information was derived from the Driller's Log and the depth-to-water was obtained (when available) from the time when the well was constructed. Additionally, aquifer test information was obtained from the lithologic log for five of the wells. The aquifer test information for these wells is summarized in Table 2. Because drillers often have their own habits regarding lithologic descriptions, the lithologic logs are only an approximation of the actual subsurface conditions.

The lithologic logs are classified by generalized sediment texture encountered by the wells into three classifications: fine grained, medium grained, and coarse grained. The fine-grained texture is classified by the presence of clay, sandy clay, and clayey sand horizons with minor amounts of sand and gravel. The medium-grained texture is classified by significant amounts of clayey sand, silty sand, and clayey gravel. The coarse-grained texture is characterized by significant amounts of sands and gravels, interbedded with fine-grained and medium-grained lithologic layers.

The collection of lithologic logs demonstrate an overall approximation of the subsurface conditions in the southern portion of the study area of being of medium texture, corresponding to an approximate hydraulic conductivity of 2 ft/day (0.6 meters/day) (Fetter, 1994). The approximated hydraulic conductivity is derived from the reported specific capacities for wells listed in Table 2 (Molycorp, 2008), which have reported specific capacities of 3.8 gal/min (14.4 L/min) and 0.8 gal/min (3.0 L/min) per 1 foot (0.304 meter) of drawdown. These specific capacities translate into transmissivities of approximately 1,100 and 240 ft^2/day (304 and 73

m^2/day). This also corresponds to hydraulic conductivities of 2.8 and 1.2 ft/day (0.85 and 0.36 m/day), respectively. Hence, the average hydraulic conductivity (K) is 2 ft/day (0.6 m/day). These K values are similar to reported values from aquifer tests in the water-supply wells conducted at the Primm Valley Golf Course (Durbin, 2007).

Additionally, while the average hydraulic conductivity of 2 ft/day (0.6 m/day) estimated by the well logs and Durbin (2007), represents the horizontal conductivity of the alluvial aquifer, the vertical conductivity, specific storage, and specific yield also are important hydraulic characteristics. The vertical conductivity represents the ability to transmit groundwater vertically (Fetter, 1994). The specific yield represents the volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table (Fetter, 1994). The specific yield is the release of groundwater from the pore spaces as the depth-to-water declines (Fetter, 1994). Based on the texture classifications and correlated to Durbin (2007), the vertical hydraulic conductivity is approximately 10 percent of the horizontal conductivity, or 0.2 ft/day (0.06 m/day), the specific storage is about 0.0001/ft (0.00003 m), and the specific yield is about 0.05 for the southern portion of the study area.

Specific capacity, hydraulic conductivity and transmissivity were estimated by Molycorp (2008) from pumping tests, and slug tests (rising and falling head) of wells in southern and northern Ivanpah Valley. The aquifer parameters were estimated by Molycorp for Jean Lake Valley to match the hydraulic gradient of the numerical groundwater model used by Molycorp (2008) with the transmissivity estimates ranging from 296 to 13,400 ft^2/day. Specific capacity results ranged from 1.47 to 66.67 gpm/ft (Molycorp 2008). The differences of these aquifer parameters are likely

due to subsurface geology of fine or coarse grained sediments encountered by the wells, the limited available data in Jean Lake Valley, and the numerical model hydraulic gradient estimates.

The 2008 Molycorp conceptual model estimates the area between the Lucy Grey Range and the McCullough Mountains as having an estimated hydraulic conductivity of 2.0×10^{-2} ft/day (0.6×10^{-2} m/day), the equivalent of fine grained texture (approximately silt). Additionally, the conceptual model shows a north-south divide of estimated hydraulic conductivity between Lucy Grey of 6.47×10^{-2} ft/day (1.97×10^{-2} m/day) and the McCullough Mountains of 1.801 ft/day (0.54 m/day). These values conflict with the results of well logs in the Jean Lake Valley area (NDWR 2013a). Field mapping conducted for this research found medium and coarse grained surficial sediments in this area. House et al. (2006c) also found similar sediments, with younger alluvial surfaces unconsolidated, while older surfaces of Plio-Pleistoncene ages being moderately consolidated. Based upon the well logs, and assuming that the surficial geological mapping for this research and that of House et al. (2006c) continue at depth, the north-south hydraulic divide between the Lucy Grey and McCullough Mountains shown in the Molycorp model appears to be arbitrary. This arbitrary divide is not considered valid, and was not used in the recharge estimates or estimated hydraulic conductivity in this research.

Table 2. Aquifer testing results from pump testing of Union Pacific and Molycorp wells (Molycorp 2008). Specific capacity of each well was calculated during the pumping tests. Transmissivity can be estimated from the pump test data utilizing the equation T = 1500 X Specific Capacity X 0.134 (Driscoll, 1989)

Well	WL (ft bgs)	Drawdown (ft)	Q (gpm)	SC (gal/ft)	T (ft^2/day)
15N 15E 56J01	186	67.1	400	5.96	1198
15N 15E 56J02	192	186.6	340	1.86	366
15N 15E 57G01	90	50	100	2	402
16N 15E 12Q02	270	9	80	8.89	1787
16N 15E 12Q03	367	56	300	5.36	1077

Molycorp Numerical Model Values of hydraulic conductivity for the study area are as follows:

North Jean Lake Valley = 6.467×10^{-2} ft/day (1.97×10^{-2} m/day).

Ivanpah Valley South/Basin # 164b = 1.801 ft/day (0.549 m/day).

Ivanpah Valley South main flow system south = 2.75×10^{-2} ft/day (0.838×10^{-2} m/day).

Ivanpah Valley North = 1.3 ft/day (0.39 m/day).

Infiltration Investigation and Runoff

Infiltration tests at four ephemeral drainage channels were planned to refine/confirm the recharge estimates provided by Glancy (1968) and Geomega (2000). These infiltration tests were intended to provide data to advance the conceptual knowledge regarding water infiltration for enhancement of natural recharge via infiltration basins or ASR storage.

As stated in Chapter Two, the test method selected to provide a field measurement of the rate of water infiltration into soils was to measure the height of ephemeral stream flow above the stream channel multiplied by the length of the runoff flow and the width of the stream channel (USGS 2014), subtracting the normal estimation for evapotranspiration using the Maxey-Eakin (1949) method during the time period of the storm event. Remote streambed loggers were deployed in four alluvial drainage channels, two in the JLV hydrographic drainage, two in the southern Ivanpah hydrographic drainage, in June of 2013. During the week of August 11 to 18, 2013, several major summer monsoonal storms entered the study area, and major runoff events flowed from drainages emanating from the McCullough Mountains. These runoff events created

significant debris flows of coarse alluvium in the four alluvial drainage channels where the loggers were located, and three loggers were washed away. Several efforts to locate the loggers were to no avail, and it is assumed the loggers were washed downstream and then buried by debris. The fourth logger was severely damaged by a large, 20 x 19 inch (50.8 x 48.3 cm) diameter boulder, and the data unrecoverable.

In lieu of direct measurements, groundwater recharge was estimated in the study area using research commissioned by Molycorp (2008).

The precipitation in the study area ranges from less than 4 inches (10.60 cm) per annum at Jean Dry Lake to 14-16 inches (35.56 to 40.64 cm) in the McCullough Mountains (Moore, 1968; Geomega, 2000). Precipitation and climatic data was obtained from nearby precipitation stations in Mountain Pass, California, Searchlight, Nevada, and Las Vegas, Nevada, essentially triangulating the study area. The Mountain Pass data was selected for this study as the most representative of the McCullough Mountains due to their proximity and similar elevation.

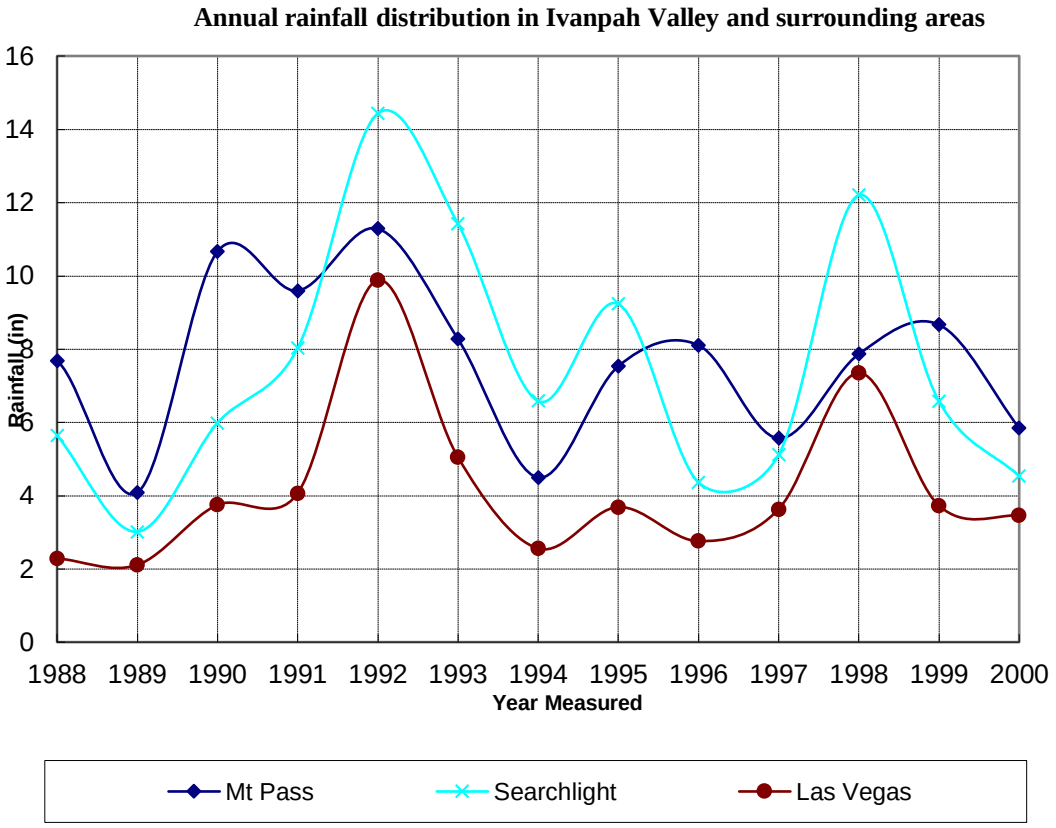

Figure 8**.** Results compiled from LVVWD data collected from precipitation stations in Mountain Pass, California, Las Vegas, Nevada, and Searchlight, Nevada. The data shows the 12 year record of annual precipitation for these areas. The runoff estimates by Geomega, 2000 for the Mountain Pass area utilized the same timeframe and dataset.

Runoff available for infiltration has been studied by Molycorp in the Mountain Pass area. The results showed that an average of 7 % of precipitation will result in runoff, but this can vary depending on the precipitation event. Runoff was found to be as high as 20 % during frequent heavy storms, and as low as 0.72 % during dry months (Molycorp, 2008). The methodology of this estimate was the aggregate of two runoff/recharge studies conducted by Geomega (2000) and Moore (1968). A comparison of two estimates are listed below in Table 3.

Table 3 (from Molycorp, 2008). Estimated runoff in the southern portion of Ivanpah Valley comparing the estimates of Moore, 1968, and Geomega, 2000. The data focuses on the Mountain Pass area on the western portion of IVS, similar in elevation and areal extent as the McCullough Mountains. The McCullough Mountains are located on the

eastern side of IVS and IVN, and the runoff estimates for the Mountain Pass area are extrapolated to the McCullough Mountains for the purposes of this research.

Molycorp 2008 Ivanpah Valley (Nevada)								
Elevation (feet)	Areal Extent (acres)	Range (inches)	Average (feet)	Acre Feet	Geomega (2000) Estimated Runoff (af.)	Moore (1968) Estimated Runoff (af.)	Geomega Estimated Recharge (af.)	Moore Estimated Recharge (af.)
> 8,000	30	16-20	1.36	41	2.86	7	-5	-1
7,000 - 8,000	780	14-16	1.27	991	69.34	98	59	86
6,000 - 7,000	3,100	12-14	1.1	3,410	238.7	181	223	167
5,000 - 6,000	10,840	10-12	0.94	10,190	713.27	271	682	254
< 5,000	135,940	< 8	0.77	104,674	0	0	-8	-8
				Totals	**1,024**	**566**	**951**	**498**

Groundwater Geochemical Results

The results of the sampling for this study, as well as incorporation of historical water quality results (Mark Group (1988), Molycorp (2008) LVVWD (2012)) found areas of distinct spatial variability of groundwater geochemical constituents within the study area (Attachment B).

Several historical sample locations incorporated into the analysis for this study have variability in completeness of their chemical constituent datasets. After standard deviation and the arithmetic mean of each constituent was calculated for the most complete data sets, three constituents were found to provide the best representation of the spatial variability in the study area (Attachment B). Chloride, magnesium, and total dissolved solids (TDS), which were found in both the sub-basin and IVN, were selected as the representative constituents for this study. Other

constituents, such as fluoride, magnesium, and calcium were also found both in IVN and the sub-basin, but little concentration variability was found in these other constituents.

The groundwater geochemistry varies widely between the main valley and the study area. Across both basins, however, dominant cations of sodium and calcium are similar in concentration, and bicarbonate is generally the major anion for both the IVFS and the study area. Simple statistical analysis of the data was used to simplify the dataset and identify the spatial variability trends from the groundwater and surface water data analysis (Attachment B).

Spatial Variability of Groundwater Chemistry Results

The groundwater chemistry of IVN and the proposed sub-basin exhibits differences in all the major constituents, however, distinct differences in the three key constituents of chloride, magnesium, and TDS are evident between the IVN as connected to the IVFS and the proposed sub-basin (Figures 9 and 10). The three key constituents significantly higher in concentration in the proposed sub-basin when compared to IVN (Figures 11, 12 and 13). Additionally, the groundwater wells SRM, SRP, J-7, and J-Fire, which are within 1.5 miles (3.3 km) east of the junction of the McCullough and Roach faults, have higher geochemical concentrations very similar to the other sample locations within the proposed sub-basin. The geochemical signatures of the Goldstrike and State wells located within one mile west of these faults have significantly less constituent concentrations and correspond with the water chemistry found in the IVFS (Figures 11, 12 and 13).

Based upon these spatial differences, The McCullough, Roach, and Stateline Faults appear to act as impediments between the Ivanpah Valley flow system and the proposed sub-basin

(Figures 11, 12 and 13). The proposed sub-basin has significantly higher concentrations of the three key constituents as opposed to the areas outside of the proposed sub-basin hydraulically connected to the IVFS. The geochemical concentrations of the key constituents are distinct across the three faults, implying the proposed sub-basin receives a different recharge source(s), most likely from the McCullough and Lucy Grey Mountains, and the overall flow system does not enter or interact with groundwaters of the proposed sub-basin.

Figure 9 - Ivanpah Valley Flow System Groundwater Profile

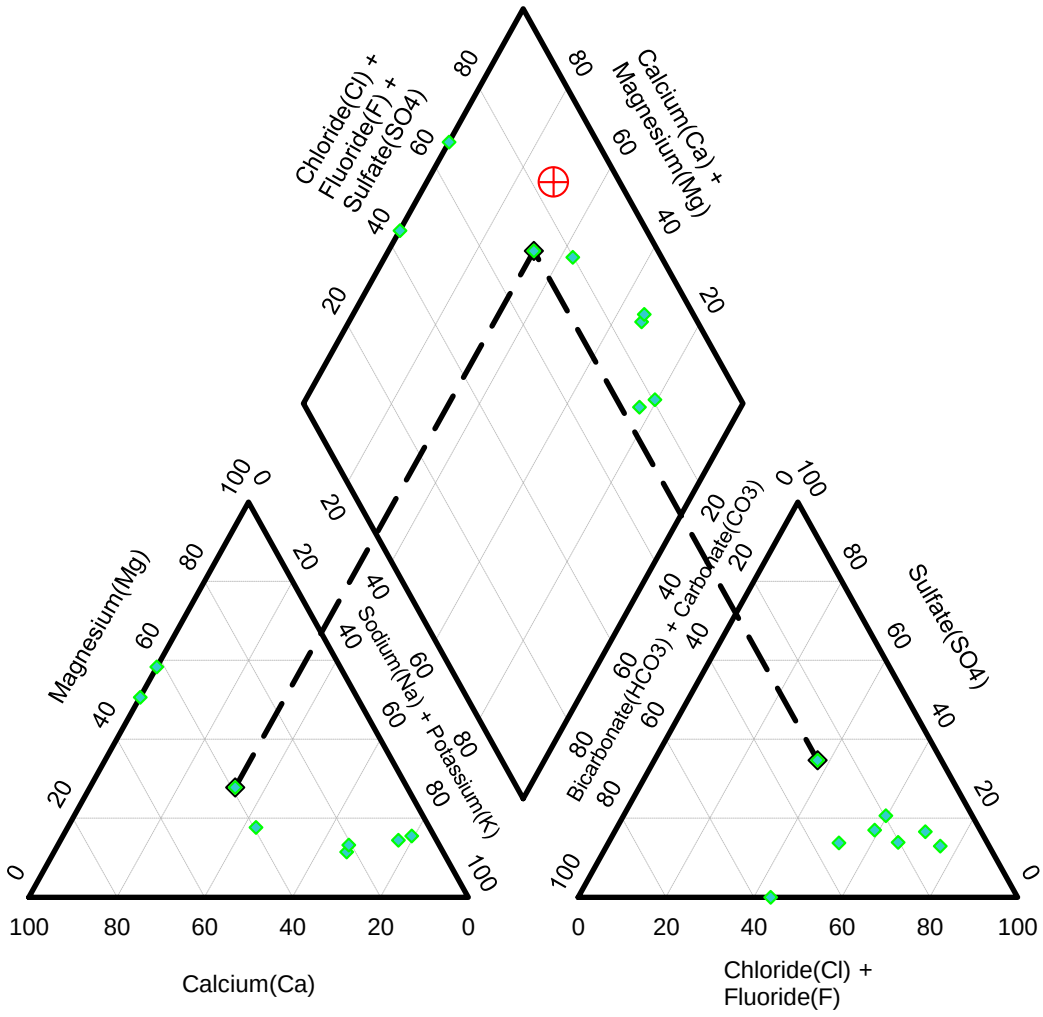

Figure 9. Piper plot of groundwater chemistry of groundwater samples from wells located in the IVFS. The geochemical results of the Goldstrike and State wells, approximately 1 mile west of the junction of the McCullough and Roach Faults, plot closely with other wells in the main portion of Ivanpah Valley rather than the samples from the proposed sub-basin.

Figure 10 - Sub-basin Groundwater Profile

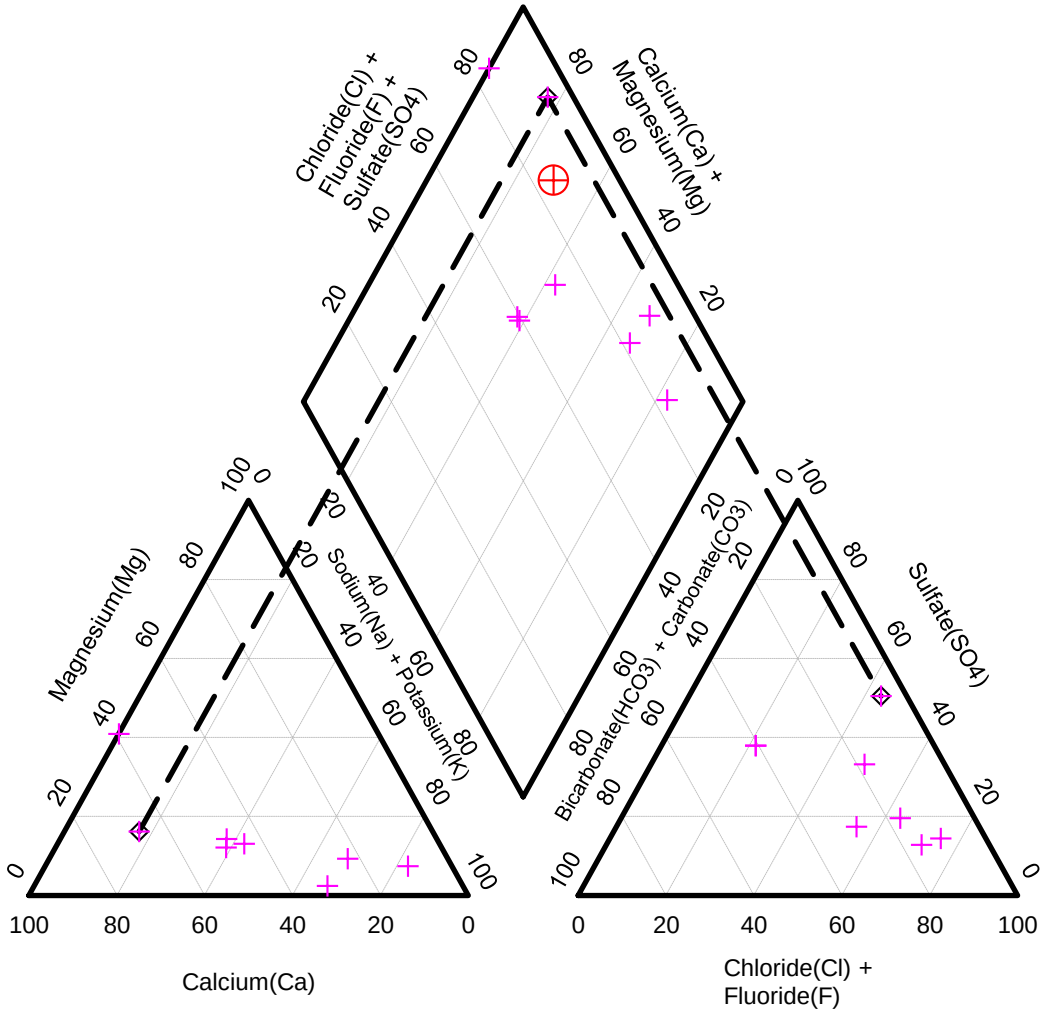

Figure 10. Piper plot of groundwater chemistry of groundwater samples from wells and springs located within the boundaries of the proposed sub-basin. Higher concentrations of Chloride and Magnesium are evident in the Piper plot of the proposed sub-basin compared to the IVFS Piper plot (Figure 6). The other constituents show similar concentrations across both the sub-basin and IVFS.

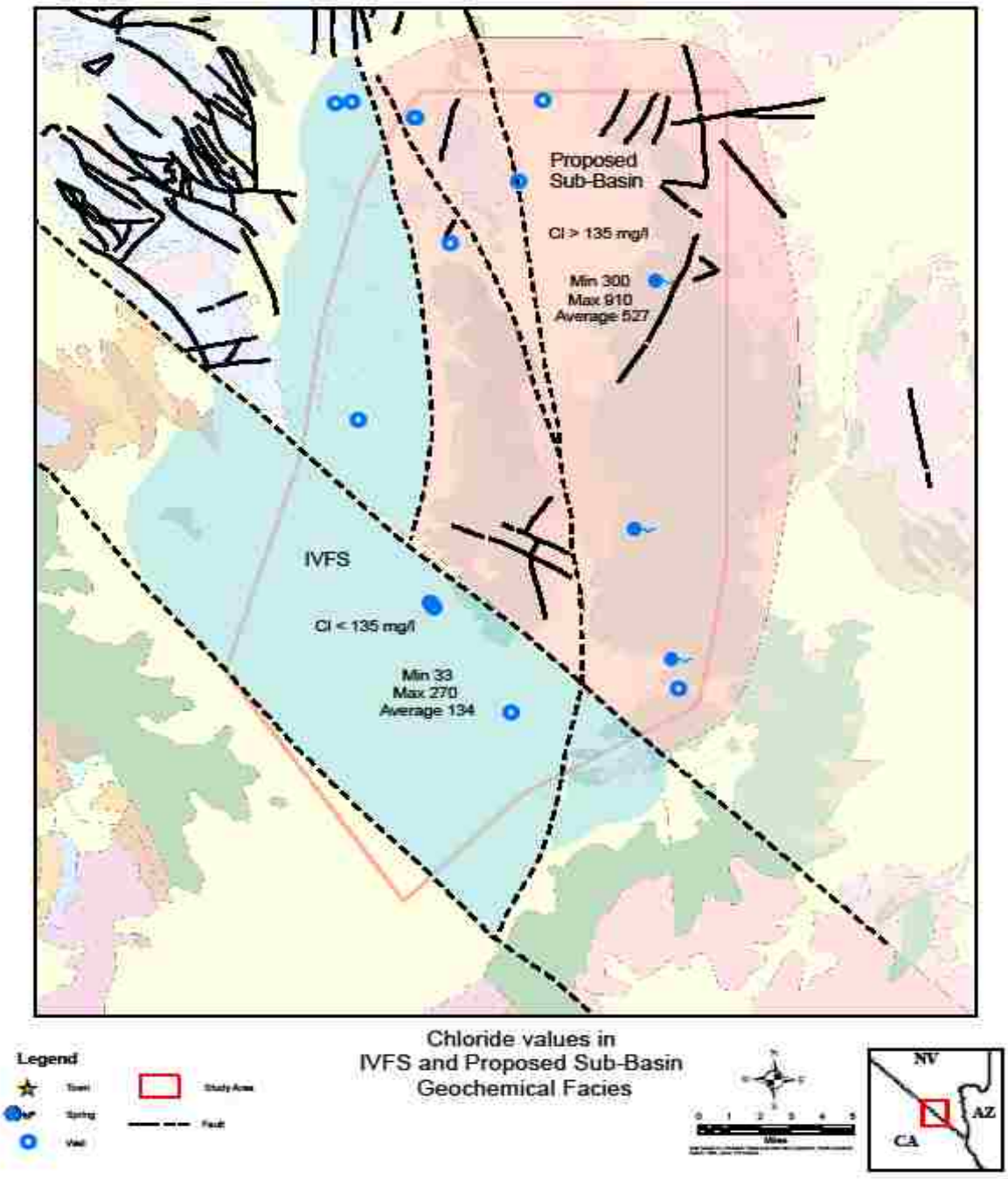

Figure 11. Chloride concentrations of groundwater in the study area showing spatial variability. Chloride concentrations are significantly higher within the proposed structurally isolated sub-basin compared to concentrations within the main portion of Ivanpah Valley.

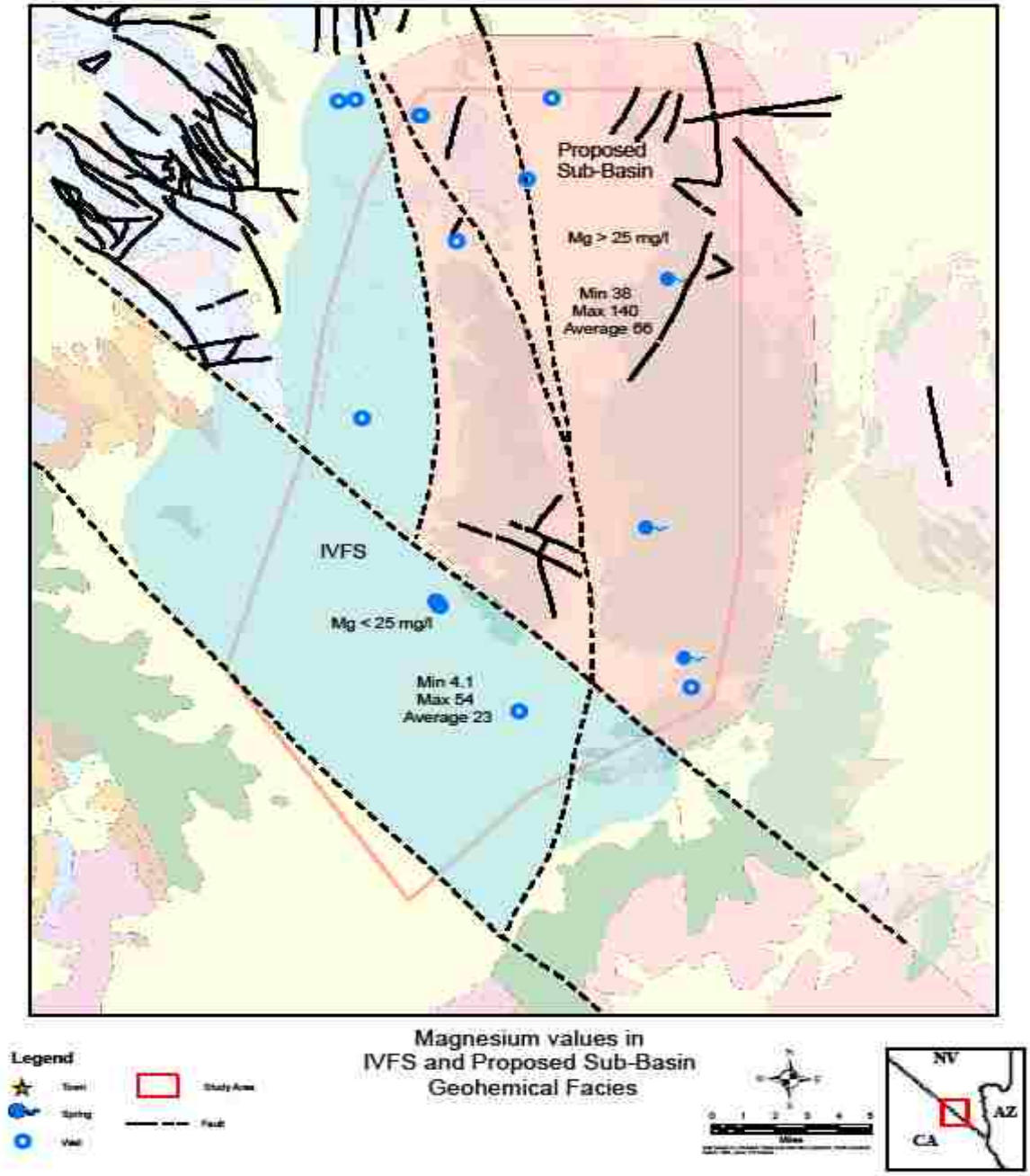

Figure 12. Magnesium concentrations of groundwater in the study area showing spatial variability. Magnesium concentrations are significantly higher within the proposed structurally isolated sub-basin compared to concentrations within the main portion of Ivanpah Valley.

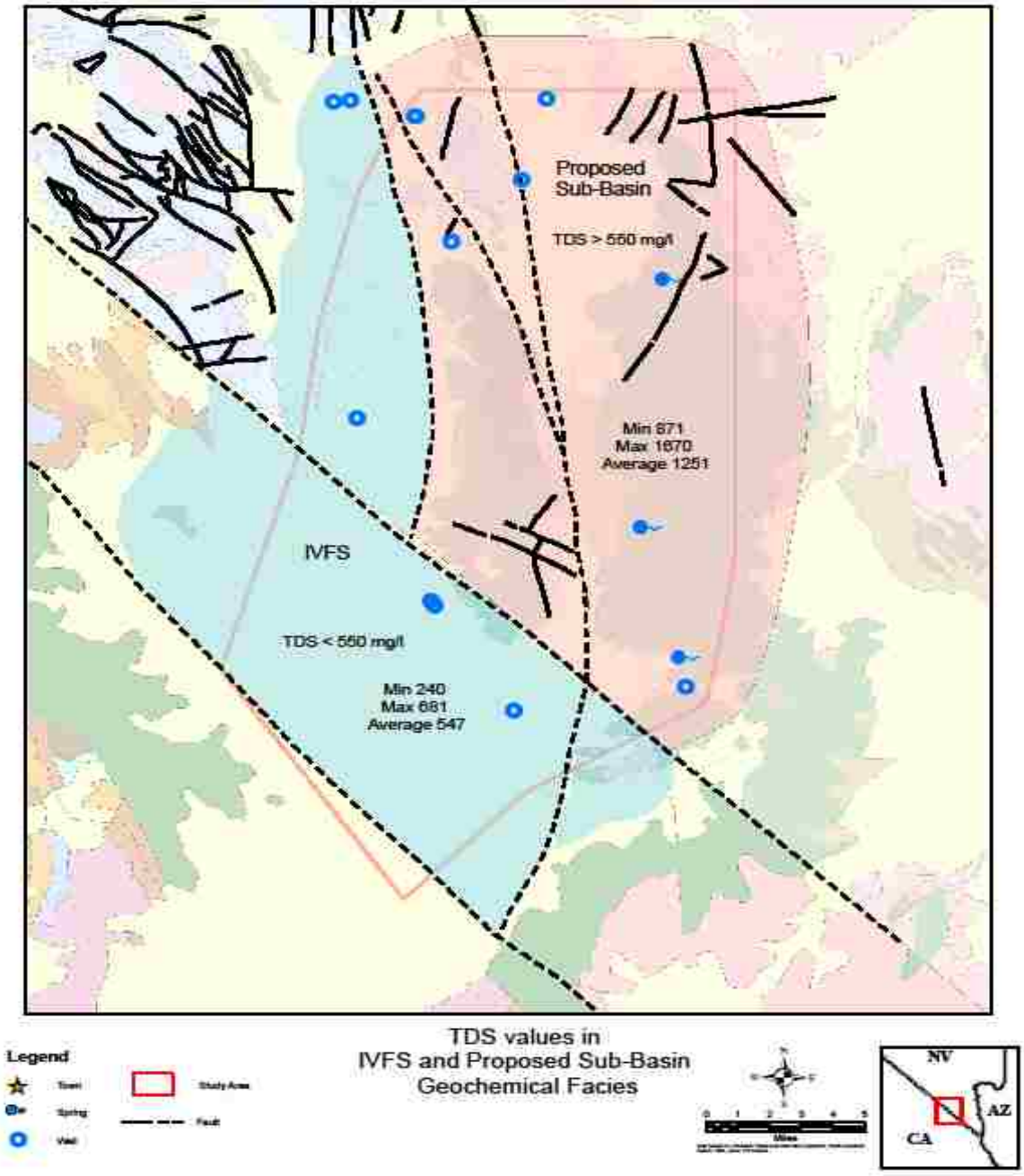

Figure 13. Total Dissolved Solids (TDS) concentrations of groundwater in the study area showing spatial variability. TDS concentrations are significantly higher within the proposed structurally isolated sub-basin compared to concentrations within the main portion of Ivanpah Valley.

Stable Isotope Results

Samples for stable isotope analysis were collected from selected springs and wells within the study area for analysis. As previously mentioned, the samples were analyzed at the Las Vegas Stable Isotope Laboratory (LVIS) at UNLV for isotopic ratios of oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$).

Stable isotopes are used to examine groundwater recharge and transport within a watershed by examining the ratios of $^{2}H/^{1}H$ (Deuterium) and $^{18}O/^{16}O$ ($\delta^{18}O$), and their distribution in relation to the local meteoric waterline. This allows insight into the environmental processes impacting the fate and transport of groundwater. Rayleigh Distillation enriches the heavier isotopes of precipitation and can be used to determine climatic and seasonal effects in the Great Basin (Lachniet, 2014).

The stable isotope values of $\delta^{18}O$ and δD samples collected during this study (Table 4) demonstrated of isotope signature typical of the Holocene aged precipitation of the Mojave Desert and southeastern Great Basin. Holocene aged precipitation ranges from -4.45 to -14.6 $\delta^{18}O$ and -30.50 to -110.99 δD (Lachniet, 2014). The sample results found groundwater to range from -9.45 to -11.6 $\delta^{18}O$ and -68.87 to -79.94 δD.

Table 4. The analysis of the stable isotopes was performed on the light stable isotope ratio mass spectrometer (IRMS) at LVIS. The IRMS measured the relative abundance of isotopes from a particular sample. The value of each sample was calibrated against known standards using a two point linear calibration.

Deuterium	**Value**	**δD (stdev)**	**Excess D**
Nipton Grocery	-79.94	1.7	-79.94
Bullion Spring	-70.10	0.5	-70.10
McClanahan Spring	-71.67	0.2	-71.67
Crestcent Well	-68.87	0.4	-68.87
δ18O	**Value**	**δ18O (stdev)**	
Nipton Grocery	-11.16	0.16	
Bullion Spring	-9.86	0.05	
McClanahan Spring	-9.45	0.08	

Crestcent Well	-9.72	0.04	

Tritium Age Date Results

The samples were analyzed at the BYU Isotope Laboratory for isotopic ratios of Tritium hydrogen (^3H), as mentioned in the previous chapter. The analysis was performed on the light isotope ratio mass spectrometer (IRMS) at BYU. The IRMS measured the relative abundance of isotopes from a particular sample.

BYU Isotope Laboratory performed analysis on a total of nine samples that were identified during the field investigation as being most spatially representative to determine groundwater pathways and travel time.

Thermonuclear Tritium is a remnant of above ground nuclear testing from the 1950s to the late 1970s and is used in groundwater studies for age dating. The radioisotope ^3H is measured using the ratio between $^3H/^1H$ using the equation (Clark, 2012):

$$^3H/^1H = 1/10^{18} = 1 \text{ Tritium Unit (TU)}$$

Tritium has a half-life of 12.32 years (Clark, 2012) and readily has entered the hydrologic cycle. Tritium can be used for age dating techniques by measuring the amount of decay. During the "Bomb Peak" in 1963, Tritium measured in North American groundwaters reached over 1,000 TU (Clark, 2012). Modern day Tritium ranges between 0.1 to 7.0 TU.

Tritium in groundwater at low levels ± 0.3 TU can be detected using electrolytic enrichment and beta counting. This method was used for the analysis of the water samples. The

BYU Isotope Laboratory reports the error as minimum detectable activity (MDA) as < 0.3 TU for the nine samples. The error could be reported as < 0.2 which is 1 sigma of statistical error (Tingey, 2014).

The nine samples had results ranging from 0.0 TU to 1.1 TU (Attachment C). Only three sample locations had TU results above the MDA as shown in the table below.

Table 5. Three samples showing results above minimum detectable activity for Tritium within the laboratory statistical error. Railroad and McClanahan Springs are upgradient in the McCullough Mountains. LVVWD Well # J-7 in Jean, Nevada is located at the base of the Sheep Range.

Railroad Spring	McClanahan Spring	LVVWD Well # J-7
0.4 TU	1.1 TU	0.5 TU

CHAPTER FIVE - DISCUSSION

McCullough and Stateline Faults

The location and orientation of McCullough and Stateline faults found during field mapping confirmed the previous projections of the faults by Schimdt and McMackin (2006). Further evidence of the presence of the McCullough Fault is supported by water level differences across the fault (Table 1). The SRM and SRP wells located on the eastern side of the McCullough Fault exhibit water levels of 2385 ft amsl (725 m amsl) and 2135 ft amsl (649 m amsl), respectively. The J-7, JGold, and JState wells west of the McCullough Fault have water levels of 2483 ft amsl (754 m amsl), 2490 ft amsl (756.9 m amsl), and 2532 ft amsl (769.7 m amsl), respectively. The static water level between these wells on opposing sides of the fault are over 100 feet (30 meters) in difference.

Geochemical Results Anomaly

One sample location within the proposed sub-basin was anomalous with the other samples within the proposed sub-basin. Bullion Spring did not exhibit the high TDS, magnesium, and chloride of any other of the samples within the proposed sub-basin, with a geochemical signature more similar to the IVFS samples. It can be assumed the water source(s) for this spring are either from the main flow system, or an entirely separate source. The former of the two is possible, due to the spring's close proximity to the Stateline fault, and mixing of the waters between the main flow system and the proposed sub-basin may be occurring. The stable isotopic values of oxygen

($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$) showing a mix of summer and winter precipitation as recharge were consistent with the other samples within the proposed sub-basin (Chapter Three).

Stable Isotope Signature

The results of the stable isotope analysis for δD and $\delta^{18}O$ was compared to the global meteoric water line (Craig, 1961) and the local meteoric waterline (Ingraham et al., 1991) utilizing the following equations:

$$\delta D = 8\delta O^{18} + 10$$

The straight line equation for the global meteoric water line (Equation 15) (Craig, 1961), and

$$\delta D = 6.87\delta O^{18} - 6.5$$

The straight line equation for the local meteoric water line (Ingraham et al., 1991).

The isotopes of $\delta^{18}O$ and δD were then compared with samples from Southern Nevada local meteoric water line from Lachniet, (2014) to determine climatological effects of groundwater recharge and determine if a Pleistocene or Holocene signature of recharge could be resolved. The stable isotope values of $\delta^{18}O$ and δD samples collected during this study (Table 3) demonstrated an isotope signature typical of the Holocene aged precipitation of the Mojave Desert and southeastern Great Basin, ranging from -9.45 to -11.6 $\delta^{18}O$ and -68.87 to 79.94 δD, and correlated to Figure 14 from Lachniet, (2014).

Figure 14 – Southern Nevada Meteoric Water Line

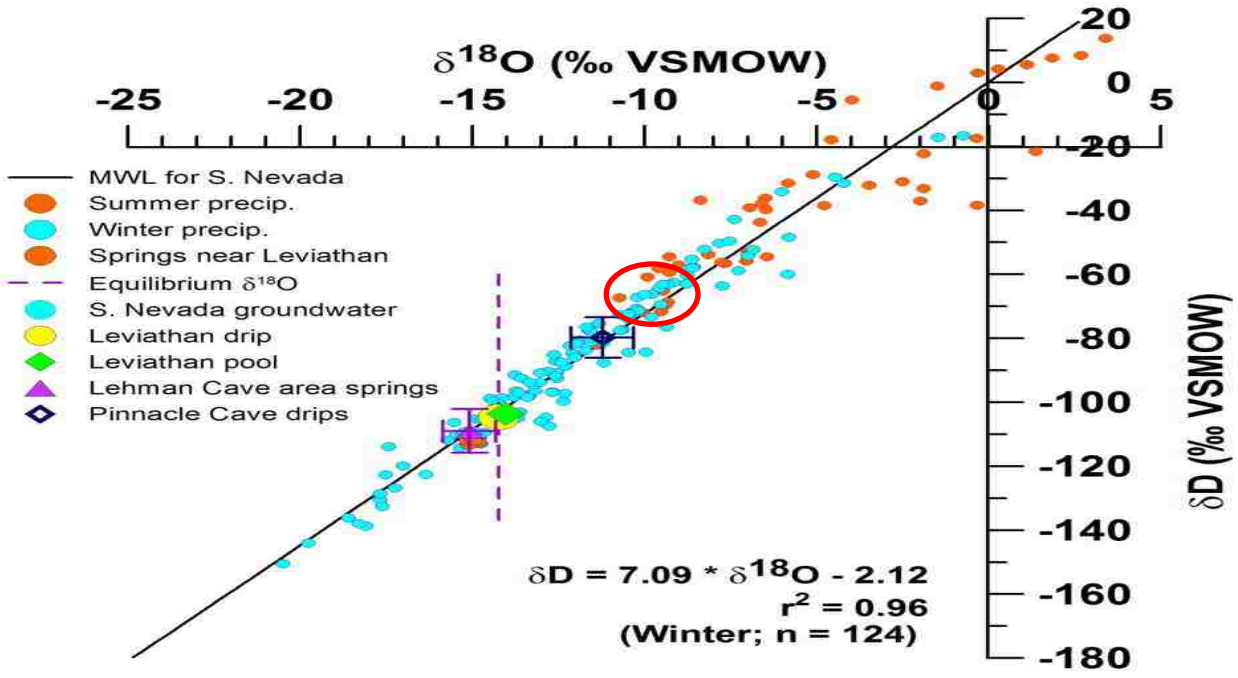

Figure 14 (Supplementary Figure 3 and caption from Lachniet, 2014). Great Basin precipitation stable isotope values. Southern Nevada meteoric water line and cave drip waters, and near-cave spring samples. The δ18O offset between the cave sites is evident in the drip (Pinnacle and Leviathan Cave; this study) and spring1 (Lehman) samples. The vertical dashed purple line is the drip water δ18O value at Leviathan Cave that is in equilibrium with measured calcite δ18O, which passes through drip water δ18O value indicating apparent isotopic equilibrium. The meteoric water line is based on winter precipitation (November through March), because summer precipitation is not a significant source of groundwater infiltration and is more affected by rain drop evaporation (caption directly from Lachniet, 2014). Results from samples collected for this research plot within the red circle superimposed upon Supplementary Figure 3 from Lachniet, 2014.

Lachniet (2014) shows the isotopic signatures of meteoric waters of southern Nevada having a generally distinct winter and summer signal. However, as is evidenced by Lachniet

(2014), mixing of seasonal isotopic signatures often occurs, primarily due to continental effects of Pacific frontal systems scooping moisture from lower latitudes during El Nino events (affectionately known as the "pineapple express") creating a source of moisture with high δ18O and δD with a southwestern flow over southern California and Arizona, thus inhibiting elevation distillation effects of the Sierra Nevada Mountains and therefore leading to winter precipitation with isotopic signatures similar to summer monsoonal moisture.

The results indicate a strong correlation to mixing of groundwater derived from seasonal precipitation patterns typical of the Mojave Desert of winter precipitation, long dry spells, and summer monsoon precipitation. Pleistocene isotopic signatures, indicative of cooler, wetter recharge of groundwater, was not discernible in the results.

Tritium Age Results and Groundwater Travel Time

The results indicate that only two springs in the McCullough Mountains and well # J-7 had detectable quantities of Tritium with an age-date of approximately 51 years. Conversely, Bullion Spring and Lucy Grey Spring, also in the McCullough Mountains, showed no detectable TU. Additionally, wells SRM and SRP nearest the McCullough Fault also had no detectable Tritium. Well J-7 is near the junction of the Roach and McCullough Faults, but given the no detectable Tritium result in the SRM and SRP wells, it is hypothesized the J-7 Tritium detection is not associated with groundwater traveling along more permeable zones along the northwest trending Roach and McCullough Faults.

The values were calculated using the following Tritium decay equations (Clark, 2012):

$$a_t\ ^3H = a_o{}^3H\ e^{-\lambda t}$$

$$t = -17.93 \ln a_t\ ^3H/a_o{}^3H$$

where a_t is the change in concentration of Tritium, and a_o is the initial concentration, and λ is equal to $\ln 2/t_{½}$ for the 12.32 year half-life.

(assumes precise input function with no mixing)

The results also indicate the other sample locations without detectable Tritium are recharged by groundwater older than 51 years, implying the estimated hydraulic conductivity of approximately 2 feet/day (0.610 m/day) can be supported (Chapter 4). Using the equation from Darcy's Law Q = KAi, the average linear velocity of groundwater can be determined = V = q/n (Fetter, 1994) where q = Ki from Darcy's Equation:

K = hydraulic conductivity = 0.610 m/day

i = hydraulic gradient (Molycorp, 2008) = Dh/Dl = 106.4 m /10,540 m = 0.01

A = Cross-sectional area near SRM well = 1000 m aquifer thickness (estimated from Langenheim, et al., 2009) x 1280m lateral distance

Therefore, the groundwater discharge is:

Q = Kai = (0.610 m/d)(1000 m x 1280 m)(0.01) = 7808 m^3/day

And the groundwater velocity = V=q/n

n = Porosity of sand = 20%

q = 0.610 m/d x 0.01 = 0.0061 m/d

V = 0.0061/0.20 = 0.03 m/d

The downgradient wells SRM and SRP, which are approximately 48,000 feet (14,592 meters) distance from Railroad Spring and 44,000 feet (13,376 meters) from McClanahan Spring

would be expected to have detectable Tritium results in approximately 1220 years, provided the wells are directly downgradient and transmissivity remains essentially constant. Given the half-life of Tritium (12.32 years), it is doubtful Tritium would be detectable after this elapsed time period. The Tritium results also support a spatial relationship between groundwaters of the proposed sub-basin and the remainder of Ivanpah Valley, and the McCullough and Roach faults acting as groundwater impediments between the proposed sub-basin and the IVFS.

ASR Potential of IVN and the Proposed Sub-basin

Evaluation of the study area as a possible location for water banking utilizing Artificial Storage and Recovery (ASR) or surface infiltration was conducted using known aquifer parameters and newly acquired data from this study to evaluate proposed sub-basin geometry, ambient water quality, and transmissivity. The success or failure of ASR in aquifer system is dependent on a wide variety of factors that are related to basin structure, hydrogeologic conditions of the aquifer(s), and engineered factors such as well design and operational parameters.

The following table (Table 5) lists the parameters governing the effectiveness of ASR (Missimer et al., 2002; Reese, 2002):

Table 6
Parameters governing ASR Effectiveness

Aquifer Parameters	Engineered Parameters
Hydraulic gradient, porosity, permeability, transmissivity Hydrodynamic Dispersion Naturally occurring water quality	Well design, Injection and Recovery flow rate Duration of injection storage and recovery Injected water quality & extraction water quality

The effectiveness of an aquifer to accept injected or percolated water (artificial recharge) is directly related to the transmissivity, groundwater velocity, and storage coefficient. The average velocity of natural groundwater flow is a function of the hydraulic conductivity, porosity, and natural gradient. The higher the natural gradient the more effectively the aquifer will accept the recharged water (Missimer et al., 2002).

The degree of mixing between the recharged water and native water and the width of the transition zone is guided by hydrodynamic dispersion, which is a reflection of the degree of spatial variability in aquifer conductivity. The mechanical dispersion is directly related to the distribution of permeability within the storage zone (Missimer et al., 2002). Higher permeability can cause higher dispersive mixing, and lower recovery efficiency. The hydraulic conductivity or permeability distribution in the storage zone greatly influences the recovery efficiency of the recharged water (Missimer et al., 2002).

Water quality of the aquifer must be acceptable for the end use of the recovered water. Ideally, the water quality of the recharged water will be geochemically similar to the naturally occurring water quality of the aquifer, with similar geochemical constituents and concentrations so as not to degrade either the recharged water or the aquifer water. The water quality of Ivanpah Valley and the IVFS is generally within US Environmental Protection Agency (USEPA) drinking water standards, dependent upon geospatial parameters of degraded water quality near playas. ASR operations using imported Colorado River Water would generally not degrade the water quality in Ivanpah Valley and the IVFS. Historically, however, treated Colorado River water injected in Las Vegas Valley has been known to form trihalomethanes (THMs) when interaction

with native groundwater occurs (Leising, 2006). If LVVWD treatment operational process were improved, the introduction of constituents which form THMs would not degrade the groundwater in Ivanpah Valley. Additionally, the degraded water quality of the proposed sub-basin found during this research would not interact with ASR water recharged in IVN or the IVFS due to the structural groundwater impediments between the proposed sub-basin and IVN.

Transmissivity Estimation

The transmissivity of an aquifer effects the ability to recharge water and recover recharged water. The transmissivity of the aquifer must be high enough to allow water to be recharged and recovered at sufficient rates to allow an ASR to economically viable (Missimer et al., 2002). Conversely, the transmissivity must be low enough to allow the recharged water to be recovered without loss due to natural gradient migration. Therefore, the transmissivity must lie within a range of values depending on the desired pumping rates and the recoverability percentage (Missimer et al., 2002).

Transmissivity and hydraulic conductivity of IVN were modeled by West Yost (2014) for the Silver State Solar Project. The transmissivity calculations were primarily based on pumping tests from wells in the IVS, using Driscoll's (1989) conversion factor for specific capacity to transmissivity. This calculation is generally considered to have significant error; however, given the limited data availability, is used as the primary sources of the simulation. The simulation anticipated groundwater drawdown due to pumping at the Silver State Solar Project east of Primm, Nevada was evaluated in five areas in Ivanpah Valley for the Silver State Solar South Project. The

pumping center was simulated to be the Silver State project well, located two miles east of Primm, Nevada.

The site was chosen by West Yost (2014) based on a radial distance of approximately 1 mile from NV Energy Higgins wells WP-1A and WP-2 in Primm, Nevada to model the impacts of the project pumping on those wells. The drawdown calculation was dependent on the hydraulic characteristics of the unconsolidated deposits (West Yost, 2014). The pumping simulation utilized the U. S. Geological Survey computer program WTAQ (Barlow and Moench, 1999) to predict the groundwater-level drawdowns in the project well and the surrounding area (West Yost, 2014). WTAQ simulated the drawdown from a pumping well in a radially symmetric three-dimensional groundwater system, where the well screen penetrates only part of the aquifer thickness. WTAQ was used to simulate pumping from a well which extends 400 feet (121 meters) below the groundwater table, on the assumption of an aquifer thickness of 1,000 feet (304 meters) at the pumping well (West Yost, 2014).

The pumping rate from the well was simulated at 200 afy (24.66 hectare meter per year) during a four-year construction period, then 2.466 hectare meter per year (20 afy) thereafter (West Yost, 2014). That pumping schedule was represented in the simulation as continuous pumping at 125 gal/min or 24,000 ft^3/day (679.68 m^3/day) and then 12.5 gal/min or 2,400 ft^3/day (67.97 m^3/day) (West Yost, 2014). After the 4 years simulation of the higher pumping rate, the drawdown in the pumping well was approximately 106 ft (32.22 m) below static water level, and the drawdown 3 miles from the well was approximately 0.01 ft (West Yost, 2014). After 4 years of a higher rate of construction pumping and then 46 years of operational pumping the drawdown in

the pumping well was approximately 11 ft (3.3 m). The drawdown 3 miles from the well was less than one foot (0.304 m) (West Yost, 2014).

Utilizing the West Yost (2014) modeling data to estimate hydraulic characteristics of the aquifer provides insight into the potential for an effective ASR operation. The results of the West Yost (2014) simulation can be used to estimate the ability of the aquifer to accept recharge water. Assuming hydraulic characteristics of injection wells are similar to pumping wells, rates of groundwater withdrawal 200 afy per year for four years and 20 afy per year thereafter (24.66 hectare meter and 2.466 hectare meter) would yield a water-level rise in the aquifer opposite of the amount of drawdown found in the simulation, by the principle of mathematical superposition if the porous medium is assumed to be homogeneous. Therefore, recharged water at these rates would raise the water-level of the aquifer approximately 11 ft (3.3 m) maximum near the alluvial material east of Primm Valley Resort, and provide an overall rise in water-levels of approximately 1 foot (0.304 m) over a large section Ivanpah Valley south of Roach Dry Lake.

Additionally, extrapolation of the simulation into areas of northeastern Ivanpah Valley with similar aquifer hydraulic properties based upon the Molycorp simulations (2008) would yield analogous results in these areas. Areas with lower hydraulic properties (i.e. permeability, porosity, gradient, and transmissivity) would be expected to prove less viable for artificial recharge operations.

Runoff and Storm Water Impoundment for Enhanced Recharge

Utilizing the runoff estimates from Molycorp (2008), if runoff was captured in earthwork infiltration impoundments (which provide storm water improvement protection for lower elevation

areas with anthropogenic development) constructed along major drainages, natural recharge could be enhanced, ranging as high as 1024 afy (126.2 hectare meter per year) (Geomega, 2000) to as low as 566 afy (69.8 hectare meter per year) (Moore, 1968), assuming minimal loss to evaporation in these impoundment ponds.

Also, areas of IVN bounded by groundwater impeding faults would allow the recharged groundwater to remain in the basin, thus increasing the groundwater in storage of the basin, and increasing the sustainable yield. If recharge were to increase using the average of the two runoff estimates of Geomega (2000) and Moore (1968) to 795 afy (98 hectare meter per year), the current annual groundwater overdraft in Ivanpah Valley (NDWR 2013) would decrease from 1,462.1 afy to 667.1 afy (180.3 to 82.25 hectare meter per year). This would increase the annual groundwater supply from 3374.3 afy to 4169.3 afy (416.05 to 514.07 hectare meter per year), leaving a remaining 667.1 afy (82.25 hectare meter per year), or within 19% of the perennial yield of the three Nevada Hydrographic Areas. As previously discussed in Chapter 2, the vertical hydraulic conductivity of IVN is approximately 0.2 ft/day (0.6 m/day). Assuming a total of 30 days of elapsed time from initial water capture behind impoundments to infiltration into the vadose zone, 6 acre feet of water per acre (0.73 hectares/m per hectare) would infiltrate. Thus, the amount of acreage required in storm water impoundments would be approximately 132.5 acres (53.53 hectares) for IVN. Using storm water impoundments would be economically favorable compared to the capital expenditures of new infrastructure for the importation of Colorado River water into Ivanpah Valley.

CHAPTER SIX – RESEARCH CONCLUSIONS

The criteria for a sub-basin is the area is isolated from regional flow by geologic structure, has a distinct geochemical groundwater signature, and has an independent source of recharge. As shown in this research, these criteria are met by the proposed sub-basin. There is supporting evidence that groundwater flow is isolated by the McCullough, Roach, and Stateline Faults. Surficial expression of these faults was mapped directly and indirectly via structural analysis. Additionally, the potentiometric surface data demonstrates a 100 to 200 foot (30 to 60 meter) difference in the groundwater depth between wells in the IVFS and the proposed sub-basin separated by the northwestern trending McCullough and Roach Faults.

The groundwater geochemistry results show distinct spatial variability between the proposed sub-basin and the remainder of Ivanpah Valley and the IVFS. Tritium age dates also indicate the groundwater recharge is localized within the proposed sub-basin boundaries. The hydraulic conductivity of the study area was estimated to be approximately 2 feet/day (0.61 m/day), based upon historical data from aquifer tests of pumping wells. The velocity of the groundwater flow was found to be 0.03 m/d (0.09 ft/day), calculated by the Tritium occurrence in upgradient springs but not in downgradient wells. Preferential groundwater pathways are therefore towards the north and south, eventually being impeded by the structural controls. However, based upon the degraded water chemistry of the groundwater in the proposed sub-basin, the sub-basin would not meet the

water quality criteria favorable to ASR operations, and it is recommended any future ASR operations are sited outside of the proposed sub-basin.

ASR operations or other artificial recharge methods to enhance the groundwater availability in IVN, outside of the proposed sub-basin boundaries, could use natural precipitation for groundwater recharge. The precipitation within the study area ranges from less than 4 inches (10.6 cm) per annum at Jean Dry Lake to 14-16 inches (35.56 to 40.64 cm) in the McCullough Mountains (Moore, 1968; Geomega, 2000). The McCullough Mountains are the primary source of groundwater recharge, due to their proximity to IVN, drainage pathways, and basin configuration. Precipitation and climatic data over a 12 year period was recorded from precipitation stations located in Mountain Pass, California, Searchlight, Nevada, and Las Vegas, Nevada, triangulating the study area. The Mountain Pass data, which is similar in elevation as McCullough Mountains, was selected as the most representative for these estimates. Utilizing the runoff estimates for the Mountain Pass area and extrapolating this data to the McCullough Mountains, a range of natural runoff between 1024 afy (126.2 hectares/m per year) (Geomega, 2000) to as low as 566 afy (69.8 hectares/m per year) (Moore, 1968) could be captured in earthwork infiltration impoundments along alluvial drainages. As shown in Figure 15, significant runoff can occur during large precipitation events.

Figure 15. Ivanpah Valley, August 4, 2014 near the California/Nevada Border. The photo shows Ivanpah Dry Lake flooded by storm water runoff which could be captured in storm water infiltration impoundments along the alluvial fans above the playa. Reports by the National Weather Service determined approximately 1 inch (2.54 cm) of cumulative precipitation had occurred in the McCullough Mountains (right side of photo) on August 3 and 4, 2014. The town of Primm, Nevada, and Interstate 15 can be observed in the distance.

Storm water capture could increase the amount of groundwater recharge by the average of the two runoff estimates to 795 afy (98 hectares/m per year) and the annual groundwater overdraft in Ivanpah Basin 164a would decrease from 1,462.1 afy to 667.1 afy (180.3 to 82.25 hectares/m per year). The groundwater supply would increase from 3374.3 afy to 4169.3 afy (416.05 to 514.07 hectares/m per year), or within 19%, of the perennial yield. Infiltration operations in IVN are feasible under the estimated vertical hydraulic conductivity of approximately 0.2 ft/day (0.06 m/day). The amount of land required for the construction of storm water impoundments for

groundwater recharge would be approximately 132.5 acres (53.53 hectares). Storm water impoundments enhancing natural recharge are economically favorable compared to capital expenditures (pipelines, lift stations, etc.) required for the importation of Colorado River water into Ivanpah Valley.

The anomalous water chemistry results found in Bullion Spring requires further study. To better understand this anomalous location, additional water samples should be collected and duplicate geochemical and isotopic analysis performed. Additionally, other geochemical parameters, such as trace mineral analysis, could be considered to isolate the possible source water for this spring.

Figure 16. Bullion Spring, IVS, near the California/Nevada Border which showed anomalous geochemistry results compared to the other sample locations within the proposed sub-basin. The sampling of all springs and wells included

field chemistry using a Hach 160NP meter collecting temperature, pH, and electroconductivity data. All samples were collected using decontaminated equipment. The family dog did not enter the spring until after sampling occurred (stepdaughter and temporary field assistant J. Peifer shown for scale).

It is recommended the hydrogeologic conditions of the sub-basin and surrounding area should be studied further if artificial recharge operations are pursued near or within the sub-basin. Additionally, further exploration of the native groundwater interaction and mixing (if any) near the McCullough, Roach, and Stateline faults should be investigated in detail. Analysis of groundwater geochemistry and the isotopic signatures of the Ivanpah Valley and the proposed sub-basin could provide additional insight into the groundwater pathways in relation to faults and other unidentified impediments/structure. The viability for artificial water storage in Ivanpah Valley would require additional investigation of both the study area and the IVFS via a comprehensive drilling, sampling, and monitoring program. Comprehensive hydraulic testing on new and existing pumping wells is needed to refine the aquifer characteristics. If the results support the findings of this thesis, it is suggested the sub-basin be named the McCullough Sub-Basin for future hydrologic studies, and be defined by the Nevada Department of Water Resources with the boundaries following the McCullough, Roach, and Stateline Faults on the west and south, the topographic divide of the McCullough Mountains as the eastern boundary, and Jean Dry Lake as the northern boundary.

APPENDIX A

NEVADA DEPARTMENT OF WATER RESOURCES MAP

APPENDIX B

GEOCHEMICAL SAMPLE RESULTS

APPENDIX C

TRITIUM SAMPLE RESULTS

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