Cadiz Groundwater Conservation and Storage Project

Prepared for

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Acronyms and Abbreviations

AF	acre-feet
AFY	acre-feet per year
ASP	aspect
BRGAP	USGS' Biological Resources National Gap Analysis Program
BLM	Bureau of Land Management
bgs	below ground surface
cm/d	centimeters per day
CPC	Climate Prediction Center
DEM	digital elevation model/map
ELEV	elevation
ft/yr	feet per year
GIS	geographic information system
gpm	gallons per minute
HUC	hydrologic unit codes
km	kilometers
km^2	square kilometers
LLNL	Lawrence Livermore National Laboratory
m	meters
mg/l	milligrams per liter
mi^2	square miles
MUID	map unit identifier
NED	National Elevation Dataset
NDVI	Normalized Difference Vegetation Index
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
PEST	parameter estimator
PRISM	Parameter-Elevation Regressions on Independent Slopes Model
SL	slope

TDS	total dissolved solids
USGS	United States Geological Survey
UTM	Universe Transverse of Mercator
WESTVEG	western region vegetation map

Executive Summary

Cadiz, Inc. owns 34,000 acres of largely contiguous land in the Cadiz and Fenner valleys, located in the eastern Mojave Desert, where they have farmed successfully for more than 15 years (Figure ES-1). Cadiz desires to develop a water conservation project that involves capturing natural recharge in the Fenner and northern Bristol valleys that would otherwise discharge to the Bristol and Cadiz dry lakes and then evaporate. In addition, Cadiz proposes to implement a groundwater storage component of the project that involves extraction of native groundwater from subsurface groundwater in storage. The company's intent is to develop storage conditions that would allow native water to be conserved and imported water to be transported, stored, and recaptured in the project area for beneficial uses, including environmental mitigation purposes.

Cadiz requested CH2M HILL to review previous studies and conduct additional studies to provide an updated assessment of 1) potential recoverable water that could be conserved over the long term (by intercepting water that would otherwise discharge by evapotranspiration from Bristol and Cadiz dry lakes) and 2) groundwater in storage in the Fenner Valley and northern Bristol Valley area. This updated assessment included collection of additional field data, development of a watershed soil-moisture budget model based on the USGS INFIL3.0 model, and development of a three-dimensional groundwater flow model, based on the USGS MODFLOW-2000 computer code, of the Fenner Gap area. The purpose of the update was to assess the quantity of groundwater flowing through the gap. The groundwater is expected to be a large part of the long-term average annual recharge to the Fenner Watershed, which is flowing toward the Bristol and Cadiz dry lakes. These assessments indicated that a reasonable estimate of potential recoverable water is 32,000 acre-feet per year and the volume of groundwater in storage is reasonably estimated to be between about 17 million to 34 million acre-feet in the alluvium of the Fenner Valley and northern Bristol Valley area.

Summary of Field Investigations

Field investigations were a part of this study and included the following activities:

- Geologic reconnaissance to directly observe geologic, hydrologic, and geomorphic features and conditions in the field
- Drilling of four boreholes to better delineate the subsurface geology and hydrogeology
- Three aquifer tests and one packer test to provide estimates of hydrogeologic properties
- Survey of wells and measurements of groundwater levels to define hydraulic gradients and groundwater level fluctuations
- Collection of water samples from new wells to assess groundwater quality

Figure ES-2 shows a geologic map of the Fenner Gap area and locations of wells, including new wells completed as a part of this study. Appendix A presents the details of the field investigations completed as part of this study. Following is a summary of findings from these field investigations.

The primary purpose of well TW-1 was to assess the hydrogeologic properties of the carbonate rock units in the Fenner Gap. A video log of the open borehole from 454 feet below ground surface (bgs) to about 1,000 feet bgs shows extensive fracturing, cavities, and dissolution features, resulting in significant secondary porosity and permeability. Approximately 500 feet of the carbonate rock unit was pumped for 3 days at 1,160 gallons per minute (gpm), which resulted in about 0.5 foot of drawdown (after an initial rise in groundwater level), demonstrating the substantial water transmitting properties of this hydrogeologic unit. This test indicated that hydraulic conductivity values of the carbonate rock units can be in excess of 1,000 feet per day.

The purpose of well TW-2 was to assess the thickness and hydrogeologic properties of the alluvium in its thicker section through the Fenner Gap. Wells TW-2 and TW-2B confirm a thickness of about 860 to 810 feet of alluvium, respectively. An aquifer test conducted for 3 days at 1,130 gpm on TW-2 indicated an average hydraulic conductivity value of about 600 feet per day, demonstrating substantial water transmitting capacity of the younger alluvium in the Fenner Gap.

Well TW-3 indicated that the eastern side of the Fenner Gap is underlain by older alluvium (fanglomerates) that are consolidated and less permeable than the younger alluvium. Packer tests in this hydrogeologic unit indicate an average hydraulic conductivity of 3.1×10^{-3} feet per day.

A recent well survey and groundwater-level measurements confirm a steep hydraulic gradient upstream of the Fenner Gap and a flattening of the gradient in and downstream of the gap, which is consistent with an increase in water transmitting properties of those hydrogologic units through and downstream of the gap.

Groundwater samples were collected from wells TW-1 and TW-2. Total dissolved solids (TDS) in groundwater samples collected from wells TW-1 and TW-2 screened in the alluvial aquifer range from 260 to 300 milligrams per liter (mg/l). The TDS of groundwater in the carbonate rock unit from well TW-1 is 220 mg/l. Overall, groundwater quality meets all primary and secondary maximum contaminant levels for those constituents analyzed in the samples collected as a part of this study (see Appendix A).

Summary of Groundwater in Storage

Estimates of the volume of groundwater in storage were updated from those developed previously by Geoscience Support Services Inc. (GSSI, 1999). These estimates were updated based on more recent field investigations conducted as a part of this study, as previously described, and recent studies conducted by the United States Geological Survey (USGS). As a part of their assessment of the geology and mineral resources of the East Mojave Scenic Area, the USGS (2006) developed estimates of the thickness of the alluvial sediments north of Interstate 40that were used in this study to refine the distribution of alluvial sediments in the Fenner Watershed. The volume of groundwater in storage is reasonably estimated to be about 17 million to 34 million acre-feet in the alluvium of the Fenner Valley and northern Bristol Valley area. Section 3 provides the details of the estimates of groundwater in storage.

Summary of Recoverable Water

Section 4 presents estimates of potentially recoverable water, water that would otherwise discharge to the Bristol and Cadiz dry lakes and then evaporate. The estimates were developed using the USGS INFIL3.0 watershed soil moisture budget model and then tested through application of the USGS MODFLOW-2000 model of groundwater flow through the Fenner Gap. Figure ES-3 conceptually illustrates groundwater occurrence and movement in the Fenner and Bristol valley areas. Groundwater originates as precipitation falling on the surrounding mountains. A portion of this precipitation infiltrates into the groundwater system as recharge, then flows, principally through alluvial and carbonate rock units and to a lesser extent through volcanic deposits, towards and through the Fenner Gap on its way to the Bristol and Cadiz dry lakes, where it ultimately evapotranspires, leaving behind salts that are carried with the groundwater.

Total recoverable water, therefore, is equal to the amount of recharge to the groundwater system in the Fenner Watershed, which is approximately equal to the amount of groundwater flow through Fenner Gap through the alluvial and carbonate rock units (flow through other rock units is expected to be substantially less than through these two hydrogeologic units). By intercepting this groundwater flow through the gap, a reduction of evapotranspiration from Bristol and Cadiz dry lakes is expected, but there would be no reduction in groundwater storage.

The USGS computer program INFIL3.0 was used to assess the quantity of recharge to the groundwater system and, therefore, recoverable water. The USGS released INFIL3.0 in 2008. INFIL3.0 is a grid-based, distributed–parameter, deterministic water-balance watershed model used to estimate the areal and temporal net infiltration below the root zone (USGS, 2008). The model is based on earlier versions of INFIL code that were developed by the USGS in cooperation with the Department of Energy to estimate net infiltration and groundwater recharge at the Yucca Mountain high-level nuclear-waste repository site in Nevada. Net infiltration is the downward movement of water that escapes below the root zone and is no longer affected by evapotranspiration and is capable of percolating to, and recharging, groundwater. Net infiltration may originate as three sources: rainfall, snow melt, and surface water runon (runoff and streamflow).

INFIL3.0 requires a number of inputs including (1) a grid (based on uniform squares over the watershed); (2) an estimate of the initial root-zone water contents; (3) a daily time-series input of total daily precipitation and maximum and minimum temperatures; and (4) a set of model input variables that define drainage basin characteristics, model coefficients for simulating evapotranspiration, drainage, and spatial distribution of daily precipitation and air temperature, average monthly atmospheric conditions, and user-defined runtime options. INFIL3.0 will compute daily, monthly, and annual average water-balance components for multi-year simulations.

Input required for INFIL3.0 was obtained from the following sources:

- National Elevation Dataset (NED) to define topography
- National Hydrologic Unit Codes (HUCs) to define watershed and sub-watershed boundaries

- San Bernardino County and the National Oceanic and Atmospheric Administration (NOAA) Climate Data Center to develop temporal and spatial distributions of daily precipitation and temperatures
- STATSGO soil database (STATSGO2, 2009) to define the distribution of soils and soil properties
- USGS and the state of California for geologic mapping, including the recent map, Preliminary Surficial Geologic Map Database of the Amboy 30x60 Minute Quadrangle, California (Bedford et al., 2006)
- WESTVEG GAP regional vegetation mapping to characterize vegetation in the area

The average annual recoverable water quantities for Fenner Watershed, Orange Blossom Wash area and combined (Fenner and Orange Blossom wash area) in total are: 30,191 acre-feet per year (AFY); 2,256 AFY; and 32,447 AFY, respectively, based on calendar years 1958 through 2007. The annual quantities vary with annual precipitation. In general, the period prior to about 1975 was much drier than the long-term average, while the period after 1975 was much wetter than average. So, the period 1958 through 2007 covers both a long-term dry and long-term wet periods.

Validation of Recoverable Water Estimate

Fenner Gap is the path of groundwater flow through alluvial and bedrock aquifers (such as carbonate units) from Fenner Valley into Bristol and Cadiz valleys. The long-term steady-state flow of groundwater through the gap is expected to be similar to long-term groundwater recharge in the Fenner Watershed. A three-dimensional groundwater flow model of the Fenner Gap area was developed for the purposes of validating the 30,000 AFY estimate of steady-state groundwater flow through Fenner Gap, previously described. The model is used to solve the inverse problem, that is, given a boundary inflow of groundwater at the north end of the gap of 30,000 AFY, and measured steady-state groundwater levels, what distribution of aquifer properties (specifically hydraulic conductivity) is required to allow for this flow and is this distribution likely given available information on aquifer properties?

The question was answered using a software program called PEST, which is often used in inverse modeling to aid in calibrating groundwater flow models. PEST is a model-independent parameter estimator (PEST) computer program that provides for nonlinear parameter estimation for use with almost any numerical model. PEST has been widely used and extensively tested since 1994 by scientists and engineers around the world working in many different fields, including biology, geophysics, geotechnical, mechanical, aeronautical and chemical engineering, ground and surface water hydrology, and other fields (Doherty, 2004). PEST is used to estimate groundwater model parameter values, such as hydraulic conductivity, where measurements of groundwater levels and stresses (such as pumping or recharge) are known. PEST calculates values of hydraulic conductivity that makes the groundwater flow model “calibrate” to the measured values. PEST makes many (often thousands) model simulation runs to find the best set of parameter values that minimizes the residuals (differences) in simulated and observed measurements (e.g., groundwater levels).

PEST was used in the Fenner Gap groundwater model to estimate hydraulic conductivity distributions for the alluvial aquifer and carbonate rock units in the Fenner Gap given the following constraints (1) areal and vertical distribution of alluvial and carbonate rock units as previously described, (2) constant head values (groundwater elevations) of 660 feet and 590 feet on the northern and west-southern boundaries, respectively, (3) a target flux across the northern boundary of 30,000 AFY, (4) target groundwater-level measurements from monitoring wells in the Fenner Gap area based on recent groundwater levels and, (5) estimates of hydraulic conductivity from aquifer tests from previous studies and as a part of this study. These PEST-estimated hydraulic conductivity values are evaluated in the context of the hydrogeology of the gap, including available aquifer test data, to determine if these parameter estimates are reasonable. If these hydraulic conductivity values are considered reasonable, then it is reasonable that groundwater flow through the Fenner Gap is 30,000 AFY.

PEST results produced two distributions of hydraulic conductivity that are both reasonable and consistent with observed data from aquifer tests, while maintaining 30,000 AFY of groundwater flow through the gap and matching observed groundwater levels in monitoring wells. Because of this match, it is reasonable to assume that 30,000 AFY is flowing through the gap and, therefore, that 30,000 AFY is a reasonable estimate of potentially recoverable water.

In total, data obtained from field investigations, INFIL3.0 watershed soil-moisture budget assessments, and Fenner Gap three-dimensional groundwater flow model simulations support a 32,000 AFY estimate of potentially recoverable water from the Fenner and northern Bristol Valley area. However, numerical models are based on simplified conceptual models of the more complex physical groundwater system and processes. Model construction and calibration results in non-unique models, which is demonstrated herein, in that two conceptual models provide a good fit to observed data (groundwater levels and range of hydraulic conductivity values). The Fenner Gap models suggest a large area of highly transmissive alluvium and carbonate rock units, especially along the eastern side of the gap, extending into the Bristol Valley. This area should be the focus of any additional field investigations as might be required for development of an operations plan and subsequent environmental impacts assessments, which also will provide further support of these potentially recoverable water estimates.

It is important to note that it was not the purpose, or within the scope, of the present study to develop an operations plan for development of the water resources or to provide an assessment of those environmental impacts associated with this development. Findings of this study are intended only to serve as a foundation for defining a groundwater conservation and storage project on lands owned by Cadiz, Inc. An operations plan that would include locations, quantities and timing of extractions, recharge, and storage and recovery operations would be the logical next step, followed by assessments of environmental impacts associated with the proposed operations. Those environmental assessments could include additional field investigations to further confirm the findings of this study and provide additional data as may be required to complete the environmental assessments.

1.0 Introduction

Cadiz, Inc. (Cadiz) owns 34,000 acres of largely contiguous land in the Cadiz and Fenner valleys, located in the eastern Mojave Desert (Figure 1-1). Under land use approvals issued by San Bernardino County, Cadiz has successfully farmed about 1,000 acres of land on the property for more than 15 years.

Cadiz recognized the potential for developing a water supply project on its properties in the early 1990s and reached out to partner with water supply agencies. Cadiz selected the Metropolitan Water District of Southern California (Metropolitan) to evaluate the feasibility of operating a groundwater storage and transfer project. The project would have involved transporting surplus Colorado River water to the project site, recharging it through a series of recharge basins, storing the water, and then extracting the stored water during times of drought. A pipeline would have been constructed from the Colorado River aqueduct to the project site to convey water across Bureau of Land Management (BLM) land to and from the project site. This project was referred to as the "Cadiz Groundwater Storage and Dry-Year Supply Program." The United States Department of Interior issued a right of entry for the pipeline after finding the proposed project would not cause any significant environmental harm. However, although the feasibility studies completed under the partnership demonstrated a significant potential for water supply development, Metropolitan decided not to pursue the project in 2001.

Cadiz continues to pursue partnerships to develop a water supply project in a different manner than the project previously contemplated with Metropolitan. In particular, Cadiz desires to emphasize water conservation that involves capturing natural recharge in the Fenner and northern Bristol valleys that would otherwise discharge to the Bristol and Cadiz dry lakes and then evaporate. The groundwater storage component involves extraction of native groundwater from groundwater in storage to develop storage conditions that would allow native water to be conserved and imported water to be transported, stored, and recaptured in the project area for beneficial uses, including environmental mitigation purposes.

Cadiz is a publicly traded renewable resources company founded in 1983. Between 1984 and 1994, Cadiz installed seven production wells to support irrigated agriculture that now extends to approximately 1,600 acres and includes table grapes, lemons, and various row crops. Currently, Cadiz is actively pursuing options to site utility-scale solar energy projects at their properties and to utilize renewable energy to power project-related facilities (such as well pumps and booster pump stations).

1.1 Purpose

The purpose of the current study is two-fold: (1) to develop an estimate of the recoverable water that can be prudently conserved over the long term (water that can be intercepted and that would otherwise flow to the Bristol and Cadiz dry lakes and evaporate) and (2) develop an estimate of groundwater in storage in the Fenner Valley and northern Bristol Valley area. This work is intended to complement and update the substantial earlier technical work conducted in connection with the evaluation the proposed joint project with Metropolitan. These recoverable water and storage estimates are a refinement on earlier work and also provide an independent basis for the ultimate development of a scope of a water supply project that includes water supply and storage components. It is not the scope of the current study to assess potential environmental impacts associated with development of a water supply project. The analysis of potential environmental impacts will be the subject of subsequent studies, based on the definition of a specific water supply project.

1.2 Scope

The scope of this study includes review of a substantial body of existing technical information developed in connection with the joint Cadiz/Metropolitan project, access to recent published reliable information from federal databases, including the United States Geological Service (USGS), the development of new data, including new field investigations, to assess recoverable water and groundwater in storage that can be used to establish the basis for defining a groundwater conservation project in the Cadiz area.

A large body of information, including data from project-specific field investigations was compiled as part of the Cadiz Groundwater Storage and Dry-Year Supply Program feasibility study. The feasibility study is presented in a report entitled *Cadiz Groundwater Storage and Dry-Year Supply Program, Environmental Planning Technical Report, Groundwater Resources*, prepared by Geoscience Support Services, Inc. (GSSI) in November 1999. GSSI included an evaluation of recoverable water and groundwater in storage as a part of their study. GSSI estimated the range of groundwater recharge to the Fenner, Bristol, and Cadiz watershed areas to be 20,000 to 58,000 acre-feet per year (AFY) and the amount of groundwater available to the project area to be 30,000 AFY. The volume of groundwater in storage within aquifers of the Fenner Watershed was estimated by GSSI to range from 13 to 23 million acre-feet (AF) and the volume of groundwater in storage in the aquifers of the project area ranges from 4 to 7 million acre-feet. Although thorough, GSSI's 1999 report was subject to review and evaluation by third parties.

The current study is focused on providing a new independent assessment of recoverable water and groundwater storage estimates presented by GSSI (1999), including their responses to critiques of their 1999 report. The specific scope of work of this study includes the following elements:

1. Review of previous studies on hydrology, geology, hydrogeology, groundwater conditions, vegetation, and land use in the Fenner, Bristol and Cadiz valleys, including the third-party reviews of the GSSI 1999 report.
2. Compilation of information regarding climate data (e.g., precipitation and temperature data), geologic investigations, data on wells, springs and groundwater conditions, soils mapping and characterization, and vegetation studies since the publishing of the earlier 1999 GSSI study.
3. Revisions to the depth to bedrock contour map and groundwater-level contour map to update estimates to groundwater in storage.

4. Application of a soil-moisture budget model, specifically INFIL3.0 published by the USGS (2008), to estimate net infiltration of water below the root zone and recoverable water in the Fenner Watershed and Orange Blossom Wash areas.
5. Survey of monitoring wells in the Fenner Gap area and measurement of groundwater levels.
6. Drilling of four deep boreholes and installation and testing of three deep wells in the Fenner Gap to further assess hydrogeologic properties and groundwater conditions in the gap, including characterization of the alluvial aquifer unit and carbonate units underlying the alluvial aquifer.
7. Preparation of detailed geologic cross-sections through the Fenner Gap based on previously published work and field investigation conducted as a part of this study.
8. Development of a local three-dimensional groundwater flow model of the Fenner Gap to estimate the likely flow of groundwater through the gap.
9. Comparison and discussion of recoverable water estimates, groundwater flow through Fenner Gap, and evaporation of water from Bristol and Cadiz dry lakes.
10. Preparation of a report to summarize information and present findings and conclusions of this study.

It is important to note that it was not the purpose or within the scope of the present study to develop an operations plan for development of the water resources or to provide and assessment of those environmental impacts associated with this development. Findings of this study are intended only to serve as a foundation for defining a groundwater conservation and storage project on lands owned by Cadiz. An operations plan that would include locations, quantities, and timing of extractions, recharge, and storage and recovery operations would be the logical next step, followed by assessments of environmental impacts associated with the proposed operations. Those environmental assessments could include additional field investigations to further confirm the findings of this study and provide additional data as may be required to complete the environmental assessments.

2.0 Setting

This section presents an overview of the setting of the larger area of study that includes the Fenner, Bristol, and Cadiz watersheds, and the focused area of study, which includes the Fenner Watershed, Orange Blossom Wash, and northwestern Cadiz Valley areas. Following is a brief overview of the physiography, climate, geology, and hydrogeology of the larger area of study. More comprehensive discussions of each of these topics can be found in GSSI's 1999 report and references cited therein, as well as references listed in each section below.

2.1 Physiography

2.1.1 Overview of Setting

Figure 2-1 shows the location of the larger area of study that includes the Fenner, Bristol, and Cadiz watersheds. These watersheds are located in the Eastern Mojave Desert, which is a part of the Basin and Range Province of the western United States. The Basin and Range Province is characterized by a series of northwest/southeast trending mountain and valleys formed largely by faulting (Burchfiel et al., 1980). One of the prominent features of the area is the Bristol Trough, a major structural depression caused by faulting (Thompson, 1929; Bassett et al., 1964; Jachens et al., 1992). The Bristol Trough encompasses the Bristol and Cadiz watersheds that together form a relatively low land area that extends from just south of Ludlow, California, on the northwest to a topographic and surface drainage divide between the Coxcomb and Iron mountains on the southwest. The Bristol and Cadiz valleys are bounded on the southwest by the Bullion, Sheep Hole, Calumet, and Coxcomb mountains and on the northeast by the Bristol, Marble, Ship, Old Woman, and Iron mountains. The Cadiz and Bristol dry lakes are separated by a low topographic and surface drainage divide.

The Fenner Watershed is located north of the Bristol Trough. This watershed encompasses approximately 1,100 square miles (mi^2). It is bounded by the Granite, Providence, and New York mountains on the west and north and the Piute, Ship, and Marble mountains on the east and south. Fenner Gap occurs between the Marble and Ship mountains, where the surface drainage exits Fenner Watershed and enters the Bristol and Cadiz watersheds. The Clipper Mountains rise from the southern portion of the watershed, just northwest of Fenner Gap.

2.1.2 Topography

Figure 2-2 shows a topographic map of the larger area of study based on the National Elevation Dataset (NED) (USGS, 2006). Figure 2-3 shows drainage areas within the Fenner, Bristol, and Cadiz watersheds based on the National Hydrologic Unit Codes (HUC) (NRCS, 2009).

The New York Mountains rise to elevations of approximately 7,532 feet above the National Geodetic Vertical Datum of 1988 (NGVD). The Granite and Providence mountains range from 6,786 feet to 7,178 feet above NVGD, respectively. The Piute Mountains range up to 4,165 feet above NVGD. The Clipper Mountains rise to an elevation of more than 4,600 feet above NVGD. Finally, the Marble and Ship mountains range up to 3,842 and 3,239 feet above NGVD, respectively. Generally, the Fenner Valley slopes southward toward the Fenner Gap, which is the surface water outlet from the valley, at an elevation of about 900 feet above NGVD.

Mountain ranges surrounding the Bristol and Cadiz watersheds are lower in elevation than those mountain ranges surrounding the Fenner Watershed. Peak elevations for these mountains include the following: Bristol, 3,422 feet above NGVD; Iron, 3,296 feet above NGVD; Bullion, 4,187 feet above NGVD; Sheep Hole, 4,685 feet above NGVD; Calumet, 1,751 feet above NGVD; and Coxcomb, 4,416 feet above NGVD.

The Bristol and Cadiz dry lakes represent the lowest elevations at 595 and 545 feet above NGVD, respectively.

2.1.3 Vegetation

Figures 2-4 and 2-4b show the distribution of vegetation in the larger area of study based on a western region vegetation map (WESTVEG) compiled as a part of the USGS's Biological Resources National Gap Analysis Program (BRGAP, 2009). The BRGAP digital vegetation maps are developed using satellite imagery and other records based on the National Vegetation Classification System (Hevesi, 2003). The WESTVEG plant associations in the larger area of study include the following: blackbush scrub, desert dry wash woodland, desert saltbrush scrub, Mojave creosote bush scrub, Mojave mixed steppe, Mojave mixed woodland and succulent scrub, Mojave mixed woody scrub, Mojavean pinyon and juniper woodland, semi-desert chaparral, and Sonoran creosote bush scrub. The Mojave creosote bush shrub is the most prevalent plant association and covers most of the valley floors; however, it is relatively sparse even in these areas. The Pinyon and juniper woodlands vegetation association occurs at higher elevations where precipitation is higher and temperatures are cooler.

2.1.4 Dry Lakes (Playas)

The Bristol and Cadiz dry lake playas are located at the lowest elevations in the larger area of study. The Bristol and Cadiz watersheds are closed, so the only natural outlets for surface water and groundwater are evaporation from the dry lake surfaces. The lake surfaces are normally dry but flash flooding from sudden spring snow thaws and/or late summer thunderstorms of high intensity can result in standing water (Bassett et al., 1959; Koehler, 1983; GSSI, 1999; Liggett, 2009).

The playas are made up of a variety of surface types, including salt crust and soft puffy porous surfaces and are largely devoid of vegetation. Clay and silts are the predominant soil types beneath the surface. Puffy surfaces are believed to be formed from capillary groundwater movement causing salts to precipitate and clays to swell on the surface, resulting in a network of polygons and hummocky relief (Czarnecki, 1997). This puffy surface is reported to cover more than 60 percent of Bristol Dry Lake (Kupfur and Basset, 1962).

2.2 Climate

The eastern Mojave Desert is characterized as an arid desert climate with low annual precipitation, low humidity, and relatively high temperatures. Winters are mild and summers are hot, with a relatively large range in daily temperatures. Temperature and precipitation vary greatly with altitude, with higher temperatures and lower precipitation at low altitudes and lower temperatures and higher precipitation at higher altitudes.

2.2.1 Precipitation

Davisson and Rose (2000) describe environmental factors that complicate the distribution of precipitation through southeastern California and western Nevada. These factors include the rain-shadow effect of the Sierra Nevada, San Gabriel, and San Bernardino mountains, and storms moving up from the Gulf of California that create more precipitation in the eastern Mojave Desert than in the western Mojave Desert. The rain-shadow effect of the Sierra Nevada Mountains has its greatest impact on precipitation just east of the Sierra Nevadas and decreases eastward into Nevada. In general, Davisson and Rose (2000) show that precipitation versus elevation is higher east of the 116^{o} W longitude than west of it. The Fenner Watershed lies to the east of this demarcation, so this watershed is expected to have higher precipitation with increases in elevation as compared to watersheds in the western Mojave Desert.

Figure 2-5 shows precipitation and temperature stations in the study area. Those stations with relatively long and complete records in the immediate area of study include Mitchell Caverns and Amboy stations. Stations with short and less complete records in the area and vicinity include the San Bernardino County stations of Goffs, Essex, and Kelso. Table 2-1 summarizes the records available for these stations. The long-term annual average precipitation at Mitchell Caverns, located at an altitude of 4,350 feet, is 10.47 inches. Amboy is represented by two stations, Amboy – Saltus Number 1, with an elevation of 624 feet and a long-term annual average precipitation of 3.28 inches (from 1967 through 1988) and Amboy – Saltus Number 2, with an elevation of 595 feet and long-term annual average precipitation of 2.71 inches (1972 through 1992)

Figure 2-6 shows isohyets of average annual precipitation for the larger area of study based on the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) map for the period 1971 through 2000. PRISM was developed by Dr. Christopher Daly of Oregon State University starting in 1991. PRISM uses point estimates of climate data and a digital elevation model (DEM) to generate estimates of climate elements, such as average annual, monthly, and event-based precipitation among other elements (www.prism.oregonstate.edu). This isohyet map shows average annual precipitation that varies from about 4 inches in Bristol Valley to more than 12 inches in the New York Mountains.

Figure 2-7 shows the cumulative departure from mean precipitation for the Mitchell Caverns and Amboy stations. The trend of relatively dry conditions prior to the mid-1970s (overall declining trend in the cumulative departure curve) and relatively wet conditions (overall rising trend in the cumulative departure curve) since the mid-1970s is typical of much of southern California.

2.2.2 Temperature

Air temperature in the eastern Mojave Desert reaches highs in the summer and lows in the winter. The average winter temperature is between 50^{o}F and 55 ^{o}F, with average daily maximum near 65 ^{o}F and average daily minimum near 40^{o} F. Average daily temperature in the summer months is over 85^{o}F, with maximum temperatures hovering around 100^{o}F and occasionally exceeding 120 °F. Average daily minimum temperatures in the summer are around 70 °F, so the range of daily temperatures may exceed 20 °F to 30°F.

The two weather stations in the area, Amboy and Mitchell Caverns, record air temperature. The minimum monthly temperature at Amboy is reported to be 50.7 °F in December and the maximum monthly temperature is 94.7 °F in July. The minimum monthly temperature at Mitchell Caverns is reported to be 46.3 °F in January and the maximum monthly temperature is 82.1 °F in July. The average annual temperatures at Amboy and Mitchell Caverns are 71.8 °F and 62.6 °F, respectively.

2.3 Geology

Information on the regional geology and structure is excerpted largely from the *Final Environmental Impact Report/Environmental Impact Statement on the Cadiz Groundwater Storage and Dry-Year Supply Program* ("Final EIR/EIS," Metropolitan, 2001) and summarized below. A recent report published by the USGS entitled: *Geology and Mineral Resources of the East Mojave National Scenic Area, San Bernardino County, California, U.S. Geological Survey Bulletin 2160* (USGS, 2006) provides additional detail on the geology and geologic structure of the northern part of the larger area of study. This report also provides additional information on the vertical extents of alluvial deposits in northern Fenner Valley that was not available during the GSSI study. In 2002, the USGS published the *Sheep Hole Mountains 30x60 Minute Quadrangle, Riverside and San Bernardino County, California* (Howard, 2002), which provides geologic details through the Bristol and Cadiz troughs, for most of the southern portion of the larger area of study. In addition, the USGS published a surficial geologic map entitled: *Preliminary Surficial Geologic Map Database of the Amboy 30x60 Minute Quadrangle, California* (Bedford et al., 2006), which covers a large portion of the area of study. This map is reproduced as Plate 1, provided in the pocket attached to this report. This later map provides valuable information on the surficial geology in the area of study.

2.3.1 Regional Geology

The larger area of study is located within the Basin and Range province of North America. Figure 2-8 is a simplified geologic map of the larger area of study showing the distribution of bedrock and alluvial/dune/lacustrine deposits. Bedrock includes igneous, metamorphic, and consolidated sedimentary rocks (including carbonates). Alluvial/dune/lacustrine deposits are unconsolidated sediments deposited by streams, wind, or in playa lakes for the purposes of this map. In general, bedrock forms the perimeter of the major watersheds. Large bedrock masses occur within watersheds, such as Clipper Mountains, which are located in the Fenner Watershed.

The Bristol and Cadiz watersheds form a broad depression that is referred to as the Bristol Trough (Thompson, 1929; Bassett et al., 1964; Jachens et al., 1992). This depression is thought to be six to ten million years old (Rosen, 1989), having formed as a result of regional movement along faults.

The crystalline basement rocks exposed in the mountain ranges of the project area consist primarily of Precambrian granitic and metamorphic rocks that are locally overlain by a sequence of Paleozoic sedimentary rocks. The Paleozoic rocks consist of sandstones, shales, slates, limestones and dolomites. These Paleozoic sediments and the underlying basement rocks have been faulted and folded by numerous periods of regional tectonism.

The crystalline basement rocks are generally much less permeable than alluvium and typically yield only small quantities of water to wells (Freiwald, 1984). Some of the Paleozoic sedimentary sections, particularly those limestone and dolomites sections that are fractured or contain solution cavities, can and do yield large quantities of water to wells, as further described in Section 4.2. Mictchell Caverns, located on the eastern side of the Providence Mountains, occur in karstic limestone of this section. The widespread distribution of these carbonate units can be seen by the distribution of other outcrops that can be found on the eastern slope of the New York Mountains, in Lanfair Valley, just north of Clipper Mountains, in the Marble Mountains, in the Ship Mountains, in the southeast end of Bristol Mountains, the Kilbeck Hills on the south, and the Old Woman Mountains on the east (see USGS, 2006; Howard, 2002; and Bedford et al., 2006, Hazzard, 1956) for locations of these carbonate units). These carbonate units are expected to be significant aquifers where dissolution features are present in the subsurface.

The basement complex and the overlying Paleozoic section were locally metamorphosed and intruded by granitic plutons during Mesozoic time. In the Old Woman Mountains, the Precambrian and Paleozoic section was also intensely deformed by ductile thrusting that accompanied the Mesozoic plutonism (Karlstrom et al., 1993). Throughout the project area, mostly fractured crystalline basement rocks form the boundaries of the groundwater aquifer system.

In the Fenner Valley, the Paleozoic section is unconformably overlain by clastic sediments and interbedded volcanic rocks of mid- to late-Tertiary age. The Tertiary volcanic rocks consist of lava flows of basaltic to andesitic composition, and pyroclastic tuffs of rhyolitic to dacitic composition. The USGS (2006) reports that a shallow trap-door caldera roughly 10 kilometers (km) in diameter is centered in the eastern Woods Mountains, based on gravity and aeromagnetic anomalies, and was formed from a major eruption 15.8 million years ago, with resurgent eruptions filling the caldera with rhyolitic flows and tuffs. Dikes of similar composition are exposed in the Marble and Ship mountains. The Tertiary sediments consist of conglomerate, fanglomerate, sandstone, siltstone, water-laid tuff, and lake sediments, which form a composite section more than 7,000 feet thick (Dibblee, 1980). The Tertiary sediments and interlayered volcanic rocks are gently dipping, due to extensional normal faulting of late-Tertiary age.

The Quaternary and late-Tertiary alluvial fill in the basins is largely derived from the Precambrian basement rocks, Paleozoic sediments, and Tertiary volcanic rocks. The USGS (2006) mapped alluvial deposits exceeding 300 meters (m) in thickness in the northern Fenner Valley (see Plate 2 provided in the pocket attached to this report and reproduced from USGS, 2006). Geophysical evidence indicates this alluvial fill locally exceeds 3,500 feet in thickness beneath a portion of the southern Fenner Valley (Maas, 1994) and even greater under Bristol Valley; a depth-to-bedrock map is shown in Section 3. These alluvial sediments form one of the principal aquifers in the study area.

The playa sediments underlying the Bristol, Cadiz and Danby dry lakes consist of brine-saturated clay, silt, fine-grained sand, and evaporite deposits. The clastic sediments were deposited when stream flow and sheet flow from the surrounding alluvial fans spread onto the playas during major storm events (Gale, 1951). The evaporite deposits formed from evaporation of both surface water and groundwater that seeps into the playa sediments from the adjacent alluvial fans (Rosen, 1989).

Bristol, Cadiz and Danby dry lakes have static groundwater levels at or near the playa surfaces (Moyle, 1967; Rosen, 1989). Sodium chloride and/or calcium chloride are currently being recovered from trenches and brine wells on all three of these playas. Thompson (1929), Gale (1951), Bassett et al. (1959), Handford (1982), and Rosen (1989) concur that the principal recharge to the playas occurs as diffuse seepage of groundwater onto the playas from the adjacent alluvial fans.

Cadiz and Bristol dry lakes are locally bordered by active dunes formed by fine to medium-grained windblown sand. These Holocene deposits overlie older playa deposits of differentiated Quaternary age (Moyle, 1967).

Amboy Crater, located near the western margin of Bristol Dry Lake, is a basaltic cinder cone and lava field believed to be as young as 6,000 years (Parker, 1963; Hazlett, 1992).

2.3.2 Structural Geology

The larger area of study is located at the eastern margin of the eastern California shear zone, a broad seismically active region dominated by northwest-trending right-lateral strike-slip faulting (Dokka and Travis, 1990). Roughly a dozen fault zones showing evidence of Quarternary movement (during the last 1.6 million years) have been identified in and adjacent to Bristol, Cadiz, and Fenner valleys (Howard and Miller, 1992).

Cadiz Valley is underlain by two major northwest-trending faults, inferred on the basis of gravity and magnetic data (Simpson et al., 1984). These fault zones have strike lengths of at least 25 miles, and may merge to the north and northwest with extensions of the Bristol-Granite Mountains and South Bristol Mountains fault zones (Howard and Miller, 1992; see the Final EIR/EIS for locations).

Right-lateral slip of as much as 16 miles along the Cadiz Valley fault zone has been postulated on the basis of correlation of a distinctive Precambrian gneiss unit across the zone (Howard and Miller, 1992). Slickenside surfaces produced by fault movement and steeply dipping sediments recovered from cored drill holes beneath Cadiz Dry Lake suggest the fault zone displaces sediments of Pleistocene age (Bassett et al., 1959).

Bristol Dry Lake is bordered by probable extensions of the Cadiz Valley and South Bristol Mountains fault zones to the east, and by probable extensions of the Broadwell Lake and Dry Lake fault zones to the west (Howard and Miller, 1992). Geophysical data indicate this structural depression may exceed 6,000 feet in depth (Simpson et al., 1984; Maas, 1994). Drill cores recovered from depths of more than 1,000 feet beneath Bristol Dry Lake suggest that subsidence of this basin began by Pliocene time and continues to the present (Rosen, 1989), and therefore may be tectonically active.

Fenner Gap appears to be a structural half-graben, formed by a system of northeast-trending, northwest-dipping normal faults, some of which are exposed in outcrops of the bedrock that flank the gap, as shown in Figure 2-9. The presence of these northeast-trending faults beneath the alluvial deposits that underlay the gap can be inferred from surface geology mapping, gravity surveys, a seismic reflection survey conducted across the gap by NORCAL Geophysical Consultants, Inc. (1997), and recent test wells drilled as a part of the this current study (see Section 4.2).

The system of normal faults that formed the half-graben of Fenner Gap displace and tilt volcanic rocks of mid- to late- Tertiary age, as shown in Figure 2-9. However, these faults do not displace Quarternary sediments and are, therefore, not considered to be either active nor potentially active.

2.3.3 Surficial Geology and Soils

This section summarizes information on surficial geology and soils in the study area.

2.3.3.1 Surficial Geology

Traditional geologic mapping often does not provide details on erosional surfaces and surface hillslope deposits. These deposits can serve as important conduits of precipitation for enhancing infiltration and groundwater recharge. Bedford et al. (2006) present a surficial geologic map of the Amboy 30x60 minute quadrangle, California. This map covers significant portions of the area of study (Plate 1 in attached pocket). Bedford et al. (2006) map two types of erosional and hillslope type deposits: abundant hillslope deposits (Holocene and Pleistocene) and Sparse hillslope deposits (Holoecene and Pleistocene). Definitions of these deposits are as follows:

- Abundant hillslope deposits - Hillslope materials such as colluvium, talus, weathering products, and landslide deposits; disaggregated cover greater than rock exposure. Generally less than 2 meters thick or patchy distribution with a small fraction of the area covered by deposits thicker than 2 meters.
- Sparse hillslope deposits – Hillslope materials such as colluvium, talus, weathering products, and landslide deposits; disaggregated cover less than rock exposure. Generally less than 2 meters thick and patchy distribution.

As shown on Plate 1 most bedrock in the area of study is mapped as abundant hillslope deposits.

2.3.3.2 Soils

The Soil Conservation Service has developed a geographical database of soils for each state called STATSGO. STATSGO provides information on soil types by a single map unit identifier (MUID). Each MUID represents a group of similar soil types. Figure 2-10 shows the distribution of MUIDs in the larger area of study from the STATSGO database.

There are 19 unique soil MUIDs in the larger area of study. Figures 2-11 and 2-12 show the percentage of grain sizes larger than 2 mm and percentage of clay for that grain size fraction less than 2 mm, respectively. In general, the soils in the area contain high percentages of coarse-grained materials and little clay in the fines (based on the fraction of materials that are less than 2 mm), based on averages using the combined weight of layer thickness and area for the soil components in each MUID. Additional soil moisture characteristics are given in Section 4.1.

2.4 Hydrogeology

The primary sources of replenishment to the groundwater system in the project area include direct infiltration of precipitation (both rainfall and snowfall) in fractured bedrock exposed in mountainous terrain and infiltration of ephemeral stream flow in sand-bottomed washes, particularly in the higher elevations of the watershed. The source of much of the groundwater recharge within the regional watershed occurs in the higher elevations (Metropolitan, 2001; USGS, 2000; Davisson and Rose, 2000).

Figure 2-13 presents a conceptualization of groundwater occurrence and movement in the area of study. Figure 2-14 presents a schematic cross-section showing occurrence of groundwater in fractured bedrock that is recharged by precipitation. Precipitation infiltrates and moves downward to the water table. In some cases, the infiltrating water may be diverted to the land surface or groundwater may intersect land surface creating a spring. Otherwise, this infiltrating water moves vertically downward where it ultimately reaches the regional groundwater system and continues to flow downgradient through principal aquifer systems.

Groundwater occurrence in fractured bedrock of the watershed-perimeter mountains has been known since before the turn of the twentieth century (Mendenhall, 1909). The USGS documented the occurrence of wells and springs (referred to as “some desert watering places”) throughout southeastern California and southwestern Nevada for the benefit of travelers and prospectors (Mendenhall, 1909). The USGS documented at least 10 wells and springs in the mountains and hills around the Fenner Watershed and a number of wells drilled into the alluvium by the Santa Fe Railroad. Another USGS study by Thompson (1929) provided additional information on more wells and springs in the study area i to survey, mark, and provide protection of watering places. Additional wells and springs were identified in the area of study and described by Thompson (1929). A more recent USGS survey of wells and springs in the area of study was conducted by Freiwald (1984). Figure 2-15 includes the distribution of wells and springs inventoried as a part of that study (USGS, 2009). These studies provide evidence of the fractured nature of the surrounding bedrock and the continuous infiltration of precipitation and movement of water through these perimeter rocks.

Although some groundwater is tapped by vegetation near the range fronts, the remainder moves slowly downgradient through Fenner Valley and Orange Blossom Wash into the Bristol and Cadiz depressions, where it eventually discharges to Bristol and Cadiz dry lakes. Evaporation of groundwater and surface water from the dry lakes over the past several million years has resulted in thick deposits of salt (primarily calcium chloride and sodium chloride) and brine-saturated sediments (Rosen, 1989).

Bristol, Cadiz, and Danby dry lakes have static groundwater levels at or near the playa surfaces (Moyle, 1967; Rosen, 1989). Sodium chloride and/or calcium chloride are currently being recovered from trenches and brine wells on all three of these playas. Thompson (1929), Gale (1951), Bassett et al. (1959), Handford (1982), and Rosen (1989) concur that the principal source of groundwater recharge to the playas occurs as diffuse seepage of groundwater into the playa sediments from the adjacent alluvial fans.

The mountain ranges that define the boundaries of the regional watersheds are comprised predominantly of granitic and metamorphic basement rock, as described previously. This less permeable basement complex forms the margins and bottoms of the aquifer systems (Freiwald, 1984). More permeable carbonate bedrock of Paleozoic age occurs locally within the boundaries of these watersheds (see previous discussion for general distribution and Section 4.2 for details in the Fenner Gap).

2.4.1 Hydrogeologic Units

Based on available geologic, hydrologic, and geophysical data, the principal formations in the study area that can readily store and transmit groundwater (aquifers) have been divided into three general units: an upper (younger) alluvial aquifer; a lower (older) alluvial aquifer; and a carbonate rock unit aquifer (principally carbonate units are aquifers, but the unit contains interbedded quartzite and shale, see Section 4.2).

The younger alluvial aquifer consists of Quaternary and late-Tertiary alluvial sediments, including stream-deposited sand and gravel with lesser amounts of silt (Moyle, 1967; GSSI, 1999). The thickness of the upper alluvial sediments ranges to approximately 1,000 feet (GSSI, 1999; Section 4.2 of this report). The lower alluvial aquifer consists of older sediments, including interbedded sand, gravel, silt, and clay of mid- to late-Tertiary age. Where these materials extend below the water table, they yield water freely to wells but generally may be less permeable than the upper aquifer sediments (Moyle, 1967; GSSI, 1999; Appendix A of this report). Production well PW-1, located in Fenner Gap, draws water primarily from the upper and lower aquifers and yields 3,000 gallons per minute (gpm) with less than 20 feet of drawdown (GSSI, 1999). The Cadiz, Inc. agricultural wells draw water from the alluvial aquifers and typically yield 1,000 to more than 2,000 gpm.

Based on findings from recent drilling in Fenner Gap, carbonate bedrock of Paleozoic age, located beneath the alluvial aquifers, contains groundwater and is considered a significant aquifer (GSSI, 1999; findings of this study as described in Section 4.2). Groundwater movement and storage in this carbonate bedrock aquifer primarily occurs in secondary porosity features (i.e., joints, faults, and dissolution cavities that have developed over time). The full extent, potential yield, and storage capacity of this carbonate aquifer have not been quantified at this time.

As previously noted, granite and metamorphic basement rock form the subsurface margins of the aquifer system. This basement rock is generally less permeable and typically yields smaller quantities of water to wells (Freiwald, 1984).

2.4.2 Groundwater Movement

In general, groundwater within the watersheds flows in the same direction as the slope of the land surface. In the Fenner Valley, groundwater generally flows southward and discharges through Fenner Gap toward Bristol and Cadiz dry lakes.

In Orange Blossom Wash, located between the Marble and Bristol mountains, groundwater flows generally southward from the Granite Mountains into Bristol Dry Lake.

Figure 2-16 presents a generalized contour map of groundwater elevations and horizontal flow directions in the area of study. The contours in this figure are based on water levels measured in more than 80 wells (GSSI, 1999). In some cases, published water level elevations have been adjusted to reflect more accurate reference elevations, obtained from updated topographic maps of the area (GSSI, 1999).

3.0 Groundwater in Storage

This section presents estimated volumes of groundwater in storage in the focused area of study: Fenner Valley and in the fresh (approximately less than 1,000 milligrams per liter [mg/l] of total dissolved solids) groundwater portion of the Orange Blossom Wash and northern Bristol Dry Lake area. GSSI (1999) estimated groundwater in storage for the alluvium of these approximate areas. Their estimate of groundwater in storage for the Fenner Valley ranges from 12,762,000 AF to 23,340,000 AF and in the area described as the "area of influence of proposed program operations," it ranges from 3,646,000 AF to 6,689,509 AF. Approximately 432,596 AF are for the carbonate unit.

Updated estimates of groundwater in storage are provided in Table 3-1. These estimates are for groundwater in storage in the alluvial aquifers and should not be taken as a total volume that could be pumped out of these alluvial aquifers. These estimates are based on independent mapping of groundwater levels and depth to bedrock as a part of this study. Groundwater-level contours were drawn from available groundwater-level data for the study area. Groundwater levels are generally consistent with GSSI (1999) groundwater-level contour maps in the southern part of Fenner Valley, Orange Blossom Wash, and northern Bristol Dry Lake area. Figure 2-16 presents this updated groundwater-level contour map. Figure 3-1 is a structure contour map on top of bedrock (or on the base of alluvial aquifers) based on geophysical surveys of Maas (1994), USGS (2006), and NORCAL (1997), and drill intercepts in the Fenner Gap (GSSI, 1999; Section 4.2.1 of this study). In addition, detailed cross-sections prepared of the Fenner Gap subsurface geology were used to develop detailed bedrock contours in the Fenner Gap area (see Section 4.2).

Figure 3-2 shows the storage zones used in the calculations of groundwater in storage. Table 3-1 also includes estimates of the following variables: volume of aquifer, determined as the volume between the groundwater table and the base of the alluvium (saturated thickness), percent of aquifer saturated thickness that is expected to be an aquifer (to exclude clay and silt intervals that do not yield water readily), and estimated specific yield. Low and high ranges are provided for each of these variables based on GSSI's (1999) previous estimates. The range of groundwater in storage in the focus area of study ranges from 16,981,600 AF to 34,415,000 AF. Approximately 12,533,800 AF to 24,407,400 AF of groundwater is in storage in the Fenner Watershed, which is comparable to those estimates provided by GSSI (1999).

These estimates of groundwater in storage are very conservative because (1) this estimate does not include the northernmost area of the Fenner Watershed due to the paucity of groundwater-level data for completing a groundwater-level contour map and (2) it does not include any storage in the carbonate aquifer or other bedrock units. Storage of groundwater in these latter units is likely to be very large. As a simple example calculation, if one assumes 500 feet of geologic materials with an effective porosity of 0.02 (2 percent) over the approximate 1,100 mi^2 watershed, the volume of groundwater in these materials would be more than 7 million AF. Again, this is not groundwater that could be completely dewatered, but it provides an indication of the vast quantities of groundwater in the watershed.

The quantities of groundwater in the area of study can be put into perspective by comparison to volumes of groundwater in storage in some of the larger groundwater basins in Southern California. Following are estimated volumes of groundwater in storage for a few basins in Southern California (Metropolitan, 2007) and for the Mojave Desert (CDWR, 2010).

Basin	Area of Basin mi^2	Groundwater Storage Capacity (AF)
Main San Gabriel	167	8,600,000
Los Angeles Coastal Plain	435	21,800,000
Orange County Basin	350	66,000,000
Chino Basin	240	6,000,000
Ventura County Basins	177	3 to >6 million
Upper Los Angeles River Area	226	3,670,000
Upper, Middle, and Lower Mojave	1,422	23,850,000

4.0 Recoverable Water

A number of attempts have been made to estimate recoverable water in the area of study. The most recent estimates are presented by GSSI (1999), USGS (2000), and Davisson and Rose (2000). GSSI (1999) based their estimates of recoverable water on a watershed model that accounts for variables affecting the daily water balance of the watershed, including precipitation, runoff, vegetation interception, infiltration, evapotranspiration, soil moisture, and percolation. GSSI estimated recoverable water for the entire Bristol, Cadiz, and Fenner watersheds to range between 19,886 to 58,268 AFY. Their estimate for the Fenner Watershed ranges from 14,646 to 37,254 AFY and for the Orange Blossom Wash area, they give a range of 1,193 to 4,285 AFY, for a combined total (Fenner and Orange Blossom) of 15,839 to 41,539 AFY.

The USGS (2000) developed a preliminary modified Maxey-Eakin model of the entire Bristol, Cadiz, and Fenner watersheds and estimated a median recharge rate of 2,550 to 11,800 AFY (2,070 to 10,343 AFY for the Fenner Watershed only). The modified model is based on a continuous exponential curve fitted to the original Maxey-Eakin step function, which is used to estimate recharge as a percentage of average annual precipitation within discrete elevation-precipitation-recharge zones.

Davisson and Rose (2000) of the Lawrence Livermore National Laboratory (LLNL) reviewed the USGS (2000) Maxey-Eakin estimates and concluded that the USGS (2000) underestimated recharge to the Fenner Watershed due to lack of geographic scale and context in their analysis of precipitation-elevation data, use of an uncalibrated Maxey-Eakin model, and lack of observational experience in the Fenner Watershed. Davisson and Rose (2000) developed a separate new Maxey-Eakin model of the Fenner Watershed. They estimated a recharge rate of 29,815 AFY based on local precipitation, but noted a worse-case scenario lower limit of 7,864 AFY, which they state is unlikely, but provided this lower number as a risk-based lower limit for use in analyses of potential environmental impacts.

Presented below is an updated estimate of recoverable water for the Fenner Watershed and Orange Blossom Wash area based on the recently released USGS (2008) INFIL3.0 model. This analysis is followed by an evaluation of groundwater flow through the Fenner Gap, which is the outlet for groundwater flow from the Fenner Watershed into the Bristol and Cadiz valleys. The analysis of groundwater flow through the Fenner Gap is used to substantiate the likely long-term quantity of recoverable water generated in the Fenner Watershed.

4.1 Application of INFIL3.0 - Watershed Soil Moisture Budget Model

INFIL3.0 is a grid-based, distributed–parameter, deterministic water-balance watershed model, released for public use by the USGS in 2008, and used to estimate the areal and temporal net infiltration below the root zone (USGS, 2008). The model is based on earlier versions of INFIL code that were developed by the USGS in cooperation with the

Department of Energy to estimate net infiltration and groundwater recharge at the Yucca Mountain high-level nuclear-waste repository site in Nevada. Net infiltration is the downward movement of water that escapes below the root zone and is no longer affected by evapotranspiration and is capable of percolating to and recharging groundwater. Net infiltration may originate as three sources: rainfall, snow melt, and surface water run-on (runoff and streamflow).

Figure 4-1 shows a schematic of the water balance processes controlling net infiltration in the INFIL3.0 model. These processes can be described in mathematical terms as follows:

$$NI_d^i = SM_d^i + RAIN_d^i + RI_d^i - D_d^i - \sum_{j=1}^{6}(\Delta w_d^i) - \sum_{j=1}^{6}(ET_d^i)_j$$

Where:

d is day

i is the cell number, grid location for the computation

NI is the total net infiltration from the bottom of the root zone

SM is snowmelt

RAIN is precipitation occurring as rain

RI is water that infiltrated the root zone from surface-water runon

D is surface-water discharge (outflow)

Δw is the change in the root-zone water storage for layer j (up to 6 layers)

ET is the evapotranspiration from layer j

INFIL3.0 computes a daily water balance on a grid overlay of a given watershed. There are several other second-level equations in the model that calculate each one of the components of Equation 1. A more detailed description of all model equations is presented in the INFIL3.0 documentation (USGS, 2008).

INFIL3.0 requires a number of inputs including (1) a grid (based on uniform squares over the watershed), (2) an estimate of the initial root-zone water contents, (3) a daily time-series input of total daily precipitation and maximum and minimum temperatures, and (4) a set of model input variables that define drainage basin characteristics, model coefficients for simulating evapotranspiration, drainage, and spatial distribution of daily precipitation and air temperature, average monthly atmospheric conditions, and user-defined runtime options. INFIL3.0 will compute daily, monthly, and annual average water-balance components for multi-year simulations.

The following section provides a summary of key inputs to INFIL3.0 for the Fenner Watershed and Orange Blossom Wash areas, used to compute recoverable water for these specific areas.

4.1.1 Model Geometry and Grid

Two model grids are used to cover the Fenner Watershed and Orange Blossom Wash areas. The model area of the Fenner Watershed is defined based on the watershed area contributing to the Fenner Gap, that is, the surface water discharge area of the Fenner Watershed. The watershed boundaries are based on the National HUCs that are extensively used throughout the United States and that were extensively reviewed to match, to a minimum, the USGS topographical 7.5 minute quads. The Fenner Watershed modeled area comprises part of the 8-digit national HUC drainage area 18100100, all the 10-digit HUC watersheds 1810010031, 1810010032, 1810010033, 1810010034, and subwatersheds located within the 1810010027 and 181001003135 watersheds. The total Fenner Watershed modeled area equals 2,816 square kilometers (km^2) or 695,845 acres.

The Orange Blossom Wash area is a much smaller area. The total Orange Blossom Wash area equals 412.75 km^2 or 101,992 acres, approximately 15 percent of the Fenner Watershed area.

Initially, the model grid resolution was defined based on the total number of cells that would have to be modeled. INFIL3.0 allows a maximum of 60,005 cells. A very fine terrain resolution is available (10-m resolution). A 500 m by 500 m grid cell resolution is selected as the input grid for the INFIL3.0 model simulations. This resolution is small enough to spatially represent all the soil, vegetation, and climate data, without major generalization of their boundaries, and large enough to provide reasonable runtimes for simulations. Figures 4-2 and 4-3 show the grid overlays used in the INFIL3.0 model simulations.

4.1.2 Topography

Topography is used in INFIL3.0 for the following purposes: estimate evapotranspiration as a function of location in the watershed (see INFIL3.0 documentation for detailed discussion of simulated evapotranspiration processes), estimate precipitation as a function of elevation (see additional details on precipitation versus elevation, below), and route runoff through the watershed.

Topography of the Fenner Watershed and Orange Blossom Wash areas, represented by a digital elevation map (DEM) file, was obtained from the National Elevation Dataset (NED) at a horizontal resolution of 10 m times 10 m. The NED is derived from diverse source data that are processed to a common coordinate system and unit of vertical measure. NED data are distributed in geographic coordinates in units of decimal degrees, and in conformance with the North American Datum of 1983 (NAD 83). All elevation values are in meters and, over the conterminous United States, are referenced to the North American Vertical Datum of 1988 (NAVD 88)(USGS, 2006a). NED data set coordinates where projected into the Universe Transverse of Mercator (UTM) Zone 11 projection, so these data could be used in INFIL3.0.

The DEM for both areas had to be converted into a x,y,z file format to be used in INFIL3.0. The Geospatial Watershed-Characteristics (GWC) file is one of the main files of the INFIL3.0 model. The GWC file requires the following parameters: CELLCODE, EASTING and NORTHING; LAT and LONG; ROW and COL; ELEV; SL; ASP; LOCID; IWAT; UPCELLS; SOILTYPE; DEPTH; ROCKTYPE; VEGTYPE: SKYVIEW RIDGE (36). Following is a brief explanation of each of these parameters. A more detailed discussion can be found in Hevesi (2008).

CELLCODE, EASTING, NORTHING, LAT, LON, grid ROW and COL are all location input parameters that are extracted from the DEM file.

Elevation (ELEV), slope (SL) (in degrees) and aspect(ASP) are all parameters derived from the DEM file and geographic information system (GIS) processing.

LOCID, is an ID number for each cell given that the DEM is sorted in descending order; therefore, the highest cell will have LOCID value 1. IWAT represents the LOCID ID of the cell that will be receiving flows from the current watershed simulation (cell at the lowest point in the watershed). UPCELLS represents the number of cells upstream from that location. All these three variable values are obtained from the DEM file using GIS processing techniques. The grid cell numbering is accomplished using a GIS flow accumulation/routing routine to ensure that INFIL3.0 routes runoff downstream through the watershed domain. Figures 4-4 and 4-5 show the flow accumulation/routing for Fenner Watershed and Orange Blossom Wash areas, respectively.

SOILTYPE is an integer code number that represents a soil type with unique properties that can be assigned to different cells in the grid. The code is linked to a soils table with specific soil parameters for each soil type within the model boundaries. DEPTH refers to soil depth in meters. Soil parameters are discussed further in Section 4.1.4.

ROCK is an integer code number that represents a unique rock type (which are geologic materials below the soil zone, so these are not necessarily rocks, but may include alluvium or other unconsolidated deposits). Each rock type code is linked to a rock type file with unique parameters of porosity, unsaturated and saturated vertical hydraulic conductivity. Rock parameters are discussed in Section 4.1.5.

VEG is an integer representing a vegetation code with unique vegetation characteristics. Vegetation parameters are discussed further below in Section 4.1.6.

SKYVIEW is total fraction of viewable sky, as fraction of hemisphere (dimensionless) (see Hevesi, 2008), which affects evapotranspiration.

RIDGE(36) are the 36 blocking ridge angles related to the SKYVIEW parameter (see Hevesi, 2008), which affects evapotranspiration.

Both SKYVIEW and RIDGE parameters are derived from a FORTRAN program that was obtained from USGS INFIL3.0 authors (Flint, 2009).

4.1.3 Climate Parameters

Two sets of climate parameters are required for INFIL3.0: monthly atmospheric conditions and daily precipitation and air temperatures (daily pairs of maximum and minimum temperature).

4.1.3.1 Monthly Atmospheric Conditions

Monthly atmospheric conditions are needed in INFIL3.0 and include monthly values of ozone layer thickness in centimeters, precipitable atmospheric water in centimeters, mean atmospheric turbidity, circumsolar radiation, and surface reflectivity. These conditions are assumed to be the same as those conditions used in previous USGS studies realized for the Death Valley, Yucca Mountain, and Joshua Tree areas in San Bernardino County (Hevesi et al., 2003; Hevesi et al., 2002; Nishikawa et al., 2004; and Rewis et al, 2006). Table 4-1 shows the model input values for each of these atmospheric conditions.

4.1.3.2 Precipitation and Air Temperature

Data sources for precipitation and air temperature include San Bernardino County, PRISM, and the National Oceanic and Atmospheric Administration (NOAA). Figure 4-6 shows all the stations, including NOAA grid locations, for which precipitation and temperature data and estimates are available and used in INFIL3.0 simulations, as described below.

San Bernardino County has six stations with precipitation and minimum and maximum temperature data. A summary of the date ranges of available data from these stations is given in Table 2-1. As indicated in Section 2, there are only a few stations in the larger area of study with long-term precipitation records.

A second source of precipitation data accessed for this study is NOAA Climate Prediction Center (CPC) .25 x .25 Daily US UNIFIED Precipitation data. The data description can be obtained from the CPC website (CPC, 2009). The CDC of NOAA dataset is derived from 3 sources: NCDC daily co-op stations (1948 through 1998), CPC dataset (River Forecast Centers data + 1st order stations - 1992 through 1998), and daily accumulations from hourly precipitation dataset (1948 through 1998). There are about 13,000 station reports each day for 1992 through 1998, and about 8,000 reports before that yielding about three times the reports of any existing historic and operational analyses as of 2000. The data were reviewed to eliminate duplicates and overlapping stations, and standard deviation and buddy checks were applied. Then they were gridded into 0.25 x 0.25, 140W-60W, 20N-60N using a Cressman Scheme. A grid of points was created in a 0.25 x 0.25 degree interval to cover areas that did not have any historical climate data and to provide interpolated values within the area of study.

CDC data were not available after 1998. Data sets after 1998 (1998 through 2008) were extrapolated by comparing annual precipitation values for Mitchell Caverns with annual precipitation values from the CDC data set. Those years from the CDC data set corresponding to comparable precipitation to Mitchell Caverns were selected as a surrogate time series and then multiplied by a scale factor so that the year average matches the true year average observed at Mitchell Caverns.

Figure 4-6 shows all the stations, including NOAA grid locations, for which precipitation and temperature data and estimates are available.

INFIL3.0 also requires monthly regression model for precipitation and air temperature to calculate daily values at each grid cell of the model. INFIL3.0 has an internal subroutine that takes into consideration grid cell elevation and the surrounding monthly precipitation from available stations when computing precipitation for a specific cell. The precipitation as a function of elevation can be estimated by a linear or quadratic function.

Average monthly precipitation and average minimum and maximum temperatures were calculated for available climate stations in the region. These monthly average data were used to develop linear equations that estimate precipitation and minimum and maximum temperature as a function of elevation for each month. Regression coefficients are derived for each month and entered into INFIL3.0's monthmod file. The equation used by INFIL3.0 is as follows:

$$E_m^i - A_m (ELEV^i) + C_m$$

where,

E_m^i is the estimated monthly climate parameter (daily precipitation or air temperature for grid location, i, and month, m

A_m and C_m are regression coefficients for each month, m

$ELEV^i$ is the elevation for grid location, i

Figure 4-7 shows the linear regression of monthly precipitation values in the area of study.

Table 4-2 shows the regression coefficients used in the monthmod table of INFIL3.0 for this study.

4.1.4 Soil Parameters

Soil data used in INFIL3.0 model simulations are obtained from the STATSGO soil database (STATSGO2, 2009) as described in Section 2. The STATSGO soil database has two components: a spatial map with polygons representing soil units (also called map units), and a database containing several tables that link to soil polygon map units. Each individual soil map polygon, or map unit, can have multiple soil components with multiple layers.

A FORTRAN program referred to as STATSGO36 (Hevesi, 2009) was used to process the STATSGO soils data and obtain soil parameters in the study area for use in INFIL3.0. STATSGO36 computes the necessary soil parameters for INFIL3.0 including, soil thickness, soil porosity, wilting-point water content, field capacity, saturated hydraulic conductivity, and drainage curve coefficient from the STATSGO database and those map units found in the modeled area. The soil thickness computed by the STATSGO36 procedure was checked against a second source that also computed weighted average soil thickness for the entire U.S. The second soils data source is available online and uses the STATSGO database to compute soil parameters that are commonly used in environmental modeling (Miller and White, 1998). The two results compare favorably for soil thicknesses of the various soil units in the study area.

There are a total of 15 different map units for the Fenner Watershed and nine for the Orange Blossom Wash area. Figure 2-10 shows the distribution of soil types in the area of study. Figure 4-8 shows the thickness of each soil map unit in the study area. Soil porosity is estimated in STATSGO36 using bulk density data from STATSGO and modified for coarse fractions (Maidment, 1993). Soil texture data are used with equations from Campbell (1985) to estimate the drainage coefficient, wilting point and field capacity. Saturated hydraulic conductivity is the layer-weighted average of the high and low values provided in the STATSGO database (Hevesi, 2009). Table 4-3 lists the soil parameter values for each soil map unit.

4.1.5 Hydrogeologic Parameters

Available geologic mapping is used to define the spatial distribution of different rock types (those geologic materials below the soil zone) in the area of study. These maps include the geologic map of California for the northernmost portion of the area and the Preliminary Surficial Geologic Map Database of the Amboy 30x60 Minute Quadrangle, California (Bedford et al., 2006). The spatial distribution of geologic units determines the values for saturated hydraulic conductivity and root zone storage capacities assigned to the bottom root zone (layer 6 in INFIL3.0) for all model grid cells.

Site-specific values of hydraulic conductivity and porosity values are not available for each lithology occurring in the area of study, except for the percolation testing in the alluvium that was completed as a part of the Cadiz Groundwater Storage and Dry-Year Supply Program (GSSI, 1999). Hydraulic conductivity and porosity values assigned to various rock types are based on a field reconnaissance and literature values for similar rock types. Bedinger et al. (1989) present hydraulic properties of rocks in the Basin and Range Province and a later study by Belcher et al., (2002) provides additional data on hydraulic conductivity distributions for comparable rocks in Death Valley as part of a regional groundwater system assessment. These studies, as well as the GSSI (1999) percolation test in the alluvium, are used as guides to defining the parameters for Table 4-4, which presents estimates of porosity and hydraulic conductivity for rock types in the area of study. In general, the saturated hydraulic conductivity is assumed to be one order of magnitude higher than the unsaturated hydraulic conductivity.

In addition to the basic rock types, the surficial geologic map of Bedford et al. (2006) discussed in Section 2.3.3 shows extensive hillslope deposits, including colluvium, talus, and other coarse-grained porous deposits throughout the area of study. These hillslope deposits are anticipated to provide conduits for precipitation to reach bedrock and infiltrate more readily than for bare exposed rocks. Therefore, those parameters given in Table 4-4 are likely to be generally more conservative than compared to parameter values that more directly accounts for these deposits.

4.1.6 Vegetation and Root Zone Parameters

The WESTVEG GAP regional vegetation map (Figure 2-4) of vegetation types is used to define estimates of vegetation cover and root zone density. Vegetation types were grouped into estimated vegetation associations that have similar root-zone depths and densities, comparable to those used by Hevesi et al., (2003) for the Death Valley region. Vegetation cover was estimated from the GAP vegetation types, using the higher values for cover. INFIL3.0 parameters for vegetation include percentage of land covered by a given type of vegetation, root density of each vegetation type for six layers, root-zone depth from land surface for Layers 1 through 5, and root-zone thickness for Layer 6. Table 4-5 shows the vegetation root zone parameters for each vegetation type in the area of study.

4.1.7 INFIL3.0 Simulation Results

Figures 4-9a through 4-9d show modeled average annual precipitation over the area of study for two time periods: 1971 through 2000 and 1958 through 2007. The first time period allows for comparison with PRISM average annual isohyets. The second time period is for the period over which recoverable water is estimated for the area of study. As shown in Figure 4-9a and 4-9b, the distribution of precipitation compares favorably with the more regional PRISM isohyets. INFIL3.0 shows slightly higher values of precipitation over the Clipper Mountains compared to PRISM. INFIL3.0 uses local elevation and precipitation relations to refine the distribution of precipitation over mountainous areas, such as the

Clipper Mountains. INFIL3.0 simulated precipitation over the Clipper Mountains is consistent with PRISM precipitation over the Old Woman Mountains, which are comparable in altitude. INFIL3.0 simulated precipitation in the Providence Mountains is also slightly higher than PRISM values, which are also due to the refinement in precipitation versus elevation modeling at this local scale and are consistent with the findings of the Davisson and Rose (2000) analysis of local precipitation compared to more regional analyses of precipitation. In general, INFIL3.0 modeled precipitation has overall lower annual average precipitation for the period 1958 through 2007, compared with the period 1971 through 2000, which is consistent with the cumulative departure from mean analysis discussed in Section 2.2.1.

INFIL3.0 simulation results for Fenner Watershed and Orange Blossom Wash Area are shown in Figures 4-10a and 4-10b, respectively. As expected, the majority of recharge occurs at higher altitudes in the mountains, where precipitation is highest and temperatures are lowest (thus lower evapotranspiration). This trend, highest infiltration at higher altitudes, is consistent for other INFIL3.0 simulations in the Basin and Range Province and southern California (e.g., Hevesi et al., 2003; Hevesi et al., 2002; Nishikawa et al., 2004; and Rewis et al, 2006).

Figures 4-11 and 4-12 show estimated annual recoverable water quantities for each area. The average annual recoverable water quantities for Fenner Watershed, Orange Blossom Wash area, and in total are 30,191 AFY, 2,256 AFY, and 32,447 AFY, respectively, based on calendar years 1958 through 2007.

4.1.8 Discussion of Recoverable Water Results

Simulation results of recoverable water using INFIL3.0 are compared to those most recent estimates of GSSI (1999), USGS (2000), and Davisson and Rose (2000) and to estimates of groundwater discharge from Bristol and Cadiz dry lakes.

4.1.8.1 Comparison to Most Recent Recoverable Water Estimates

INFIL3.0 simulation results compare favorably to GSSI (1999) watershed water balance modeling results and the Davisson and Rose (2000) Maxey-Eakin recoverable water estimate of 29,815 AFY, and are much higher than the USGS (2000) Maxey-Eakin model estimates of 2,070 to 10,343 AFY (for the Fenner Watershed only).

Figures 4-13 through 4-16 compare the INFIL3.0 simulation results against GSSI (1999) high and low estimates of recoverable water for the Fenner Watershed and Orange Blossom Wash areas. GSSI (1999) presented estimates of recoverable water for a range of model input parameters, with field capacity and soil thickness showing the greatest impacts on their estimates. GSSI (1999) changed parameters over the entire watershed to observe sensitivities, when in actuality, those changes would not likely change from the mean values over the entire watershed, but likely vary lower and higher around the mean value across the watershed, which is why GSSI (1999) selected the middle or mean value as the expected value of recoverable water. In general, INFIL3.0 results, which also uses expected values (or means) for input parameters, tracks between these two recoverable water estimates as expected, even though results are based on a completely different set of numerical algorithms. However, INFIL3.0 simulation results show significantly less spiking in infiltration during wet years as compared to GSSI's (1999) high infiltration case. The

INFIL3.0 annual spikes (highest infiltration rates) compare more closely to the highest spikes (highest infiltration) of GSSI's low-estimate case. This is true for both the Fenner Watershed and Orange Blossom Wash area.

The INFIL3.0 simulation results are based on setting IROUT equal to 1 (see USGS, 2008, for full discussion of model input options). By setting IROUT equal to 1, INFIL3.0 will route daily runoff to downstream cells as surface water runon. Runon can infiltrate back to the root zone and contribute to net infiltration. The INFIL3.0 simulation, with IROUT equal to 1, results in no surface water outflow from the watershed; that is, all runoff generated at model cells is infiltrated downstream before it can leave the watershed. INFIL3.0 simulations were conducted using IROUT equal to 0 for both the Fenner and Orange Blossom Wash watersheds. For the case with IROUT equal to 0, INFIL3.0 routes all generated runoff downstream and out of the watershed so it is not allowed to infiltrate at downstream grid cells. These INFIL3.0 simulations generated 28,380 AFY and 2,060 AFY of net infiltration and runoff out of the watershed, respectively, for the Fenner Watershed and 2,170 AFY and 90 AFY of net infiltration and runoff out of the watershed, respectively, for the Orange Blossom Wash area. Field observations after rainfall events indicate generation of runoff in washes in the Fenner Gap area, as reported in previous studies and observed during this study. Therefore, the division of total recoverable water is likely to lie between these two extremes of runoff conditions.

As stated in the introduction to this section, the USGS (2000) used precipitation data from a very large regional area, including data from precipitation stations west of the 116^{o} W longitude to compute an elevation-precipitation relation for their Maxey-Eakin model. As demonstrated by Davisson and Rose (2000), the USGS (2000) estimates are too low due to lack of geographic scale and context in their analysis of precipitation-elevation data, use of an uncalibrated Maxey-Eakin model, and lack of observational experience in the Fenner Watershed. The Davisson and Rose (2000) estimate of 29,815 AFY of recoverable water is similar to the estimate developed in this and GSSI (1999) studies.

4.1.8.2 Groundwater Discharge at Dry Lakes

Bristol and Cadiz dry lake playas are areas of groundwater discharge in the larger area of study. Groundwater flow from the Fenner Watershed is expected to be the most significant source of groundwater that is evapotranspired at these dry lake playas. The relative significance is shown by GSSI (1999), who estimated that Fenner and Orange Blossom wash areas contributed approximately 74 percent of the recoverable water in the larger area of study.

A qualitative assessment was undertaken to assess the occurrence of moist soils at Bristol and Cadiz dry lake. This assessment was made using a Normalized Difference Vegetation Index (NDVI). NDVI gives a measure of vegetation cover on the land surface over wide areas. Dense vegetation shows up very strongly in the imagery and areas with little or no vegetation are also clearly identified. Negative NDVI values indicate the presence of water, snow, or clouds.

Vegetation differs from other land surfaces because it tends to strongly absorb the red wavelengths of sunlight and reflect in the near-infrared wavelengths. Water and moist soils have more reflectance in the red wavelengths than the near infrared, while the difference is almost zero for rock and bare soil. NDVI takes values between -1 and 1, with vegetation

NDVI values typically from 0.1 up to 0.6, with higher values associated with greater density and greenness of the plant canopy. Surrounding soil and rock values are close to zero while the differential for water bodies such as rivers and lakes have the opposite trend to vegetation and the index is negative.

The NDVI formula is given by the equation (NIR-RED/NIR+RED), where RED and NIR correspond to Channels 3 and 4, respectively, for Landsat TM Satellite images.

In this study, we have used six Landsat TM satellite images to produce NDVIs. A classification system was designed using the unsupervised classification method and ERDAS software to differentiate between the land cover types within the larger area of study. Four NDVI classes were created for each subset image. Class 1 NDVI values range between -1 to -0.2 and indicate the presence of water; Class 2 values (-0.2 to 0) indicate the presence of moist and humid soils. Class 3 (0 to 0.1) is a combination of bare soil and rocks. NDVI values higher than 0.1 were combined in Class 4 and classified as vegetation. Figures 4-17 through 4-22 present the results of this analysis for Landsat TM Satellite images, including: May 16, 1990, March 16, 1991, May 19, 1991, March 10, 1992, May 14, 2005, and August 13, 2005. In all of these images, Bristol and Cadiz dry lakes stand out as having the lowest NDVI values (indicating very moist soils or water near the surface).

GSSI (2000) developed a range of estimates of evapotranspiration from Bristol and Cadiz dry lakes, using three different methods. They estimate a range of 11,665 AFY to 105,436 AFY. The upper range of values are based on evapotranspiration estimates at Franklin Dry Lake playa by Czarnecki (1997), who used energy-balance eddy-correlation techniques to estimate evapotranspiration from the playa lake surface, which resulted in evapotranspiration rates of 0.1 to 0.3 centimeters per day (cm/d) (approximately 1.2 to 3.6 feet per year [ft/yr]).

The USGS (Laczniak et al., 2001) has estimated evapotranspiration for a number of areas in the Death Valley regional flow system, which includes estimates for open playas similar to the Bristol and Cadiz dry lakes. The USGS estimated evapotranspiration rates range from 0.1 to 0.7 ft/yr . They adjust these evapotranspiration rates by the estimated long-term average annual precipitation rate (by subtracting the precipitation rate) to get evapotranspiration rates ranging from 0.15 to 0.21 ft/yr. However, Laczniak et al. (2001) state that the contribution of precipitation to evapotranspiration is uncertain. Given the high rate of evaporation in these arid environments, precipitation may not effect the evapotranspiration rates as estimated from micrometerological measurements. Using a range of 0.1 to 0.7 ft/yr (which are those estimated evapotranspiration rates from measured micrometeorological parameters) gives a range of evapotranspiration rates of 5,965 to 41,755 AFY for the Bristol and Cadiz dry lakes. Actual evapotranspiration rates are determined by site-specific conditions; however, it seems plausible that groundwater discharge from the Bristol and Cadiz dry lakes exceeds the recoverable water estimates for Fenner Watershed and Orange Blossom Wash area.

4.2 Groundwater Flow through Fenner Gap

Fenner Gap is the path of groundwater flow through alluvial and bedrock aquifers (such as carbonate rock units) from Fenner Valley into the Bristol and Cadiz valleys. The long-term steady-state flow of groundwater through the gap is expected to be similar to, and represent long-term groundwater recharge in the Fenner Watershed. A three-dimensional groundwater flow model of the Fenner Gap area was developed for the purposes of validating the 30,000 AFY estimate of steady-state groundwater flow through Fenner Gap, as previously described. The following sections provide a brief description of the local hydrogeology of the Fenner Gap, development of a three-dimensional groundwater flow model, and inverse modeling to assess the potential groundwater flow through the gap.

4.2.1 Local Hydrogeology of the Fenner Gap Area

The Fenner Gap occurs between the Marble Mountains on the west and the Ship Mountains on the east, with an alluvial plain in between these mountains as shown in Figure 4-23. Available geologic maps (e.g., GSSI, 1999; Liggett, 2010; Bishop, 1963), surface geophysical surveys (GSSI, 1999), field mapping done as part of this study, previous drilling and aquifer test data, and drilling and aquifer testing as a part of this study were synthesized to develop a conceptual model of the hydrogeology of the Fenner Gap area.

The following formations are present in the Fenner Gap area (Hall, 2007; Hazzard, 1933; Murbach and Baldwin, 1994; and Bishop, 1963): Precambrian granitic rocks in the southern Marble Mountains; Lower Cambrian rocks, including Zabriskie quartzite, Latham shale, and Chambless limestone; Middle Cambrian rocks, including the Cadiz Formation and Bonanza King Formation; Upper Paleozoic (Pennsylvanian and Permian(?)) carbonate rocks (Goodsprings Formation(?) (Hazzard, 1933, and Bishop, 1963); Mesozoic granitic rocks (Ship Mountains); Tertiary volcanics, Plio-Peistocene older alluvium, and Holocene alluvium. Figure 4-24 provides a generalized stratigraphic column of geologic units in the Fenner Gap area, and Table 4-6 summarizes the characteristics of these units, including their range of thickness.

In general, those geologic units considered most important for transmitting and storing groundwater in the Fenner Gap are the younger alluvium (referred to as “alluvium” herein) and those carbonate rocks (limestone and dolomite) within the Paleozoic sequence. Carbonate rocks in this region have been subjected to dissolution and karstification, which is evidenced by the Mitchell Caverns in the nearby Providence Mountains (Hall, 2007) and in field and well video log observations made as a part of this study (see Appendix A). Field testing, as done in previous studies and as a part of this study, demonstrate substantial water transmitting and storage properties of these units (see Appendix A). Those granitic rocks, Cambrian shales and metamorphic rocks, Tertiary volcanics and older alluvium are not expected to transmit or store water in significant quantities as compared to these other geologic units; however, there could be significant flow along fracture zones, possibly associated with faulting. For purposes of this study, the younger alluvium and carbonates rocks (limestones and dolomites) are considered aquifers. The Paleozoic sequence includes a series of carbonate units, quartzites, and shales, however, it is not practical to differentiate the various lithologic units into multiple hydrogeologic units, so the whole sequence is treated as one hydrogeologic unit and referred to as the Carbonate Rock unit. In addition, Younger Alluvium transitions to a more complex sequence of younger alluvium, older alluvium, interbedded volcanics, and possibly lacustrine deposits to the north and south of the Fenner Gap area. However, for purposes of this assessment, these finer details are not considered significant for assessing groundwater flow through the Fenner Gap as discussed in Subsection 4.2.4 below.

A series of normal faults underlie the Fenner Gap area (see Figure 4-23) and have a significant effect on the distribution of the Carbonate Rock units. Figures 4-25 through 4-32 are cross-sections through the Fenner Gap, showing the distribution of hydrogeologic units in the subsurface. These cross-sections illustrate the significant occurrence of Carbonate Rock units in the southern Marble Mountains and along the western flank of Ship Mountain. Thick sections of Carbonate Rock units dip easterly off of the northern and eastern flanks of the Marble Mountains, extending northward under the Fenner Watershed. Similarly, Carbonate Rock units dip easterly (steeply in most cases), with significant fault offsets (as much as 2,500 feet) beneath Fenner Gap. In some cases, faulting has resulted in basement rock being in direct contact with the Alluvial aquifer unit. For example, granitic rocks were encountered below about 860 feet below ground surface (bgs) in test well TW-2 and exploratory borehole TW-2B (see Appendix A). These Carbonate Rock units are projected to terminate just south of the Fenner Gap due to down-cutting and erosion by an ancestral stream through the gap. Cross-sections I-I′ and J-J′ show our projection of a few remaining remnants of the Carbonate Rock units at these section lines.

The Alluvium unit extends north-south through the gap. The Alluvial aquifer unit is thicker to the north, in the Fenner Watershed, and south of the gap, in the Bristol and Cadiz valleys. Cross-section D-D′ appears to be located along the apparent crest of the bedrock high across the gap. Older alluvium is shown in Cross-sections E-E′, B1-B1′, and D-D′ on the Ship Mountain side. Highly consolidated fanglomerates were encountered during drilling of TW-3 as a part of this study. These fanglomerates are interpreted to be Plio-Pliestocene alluvial deposits that have undergone consolidation over time. Core from TW-3 show fractures that extend through the matrix and even across individual cobbles. As shown in the cross-sections, it is interpreted that these fanglomerates were likely removed by down-cutting and erosion from an ancestral stream; younger alluvium was then deposited across the gap. The deepest part of the Alluvial aquifer unit appears to be somewhat coincident with the current Schulyler Wash.

Figures 4-33 through 4-37 show contour maps of the base of the Alluvial aquifer unit, saturated thickness of the Alluvial aquifer unit, base of older alluvium, thickness of the Carbonate Rock unit, and base of Carbonate Rock unit, respectively. As shown in Figures 4-33 and 4-34, the Alluvial aquifer unit is deepest (and thicker) along an axis that roughly parallels the Schulyler Wash though the gap. Figure 4-35 shows the extent of the old alluvium, but more specifically the projected extents of the consolidated fanglomerates encountered in TW-3. Figure 4-36 and 4-37 shows the extent of the Carbonate Rock unit and its variation in thickness in the Fenner Gap area, which is largely controlled by the series of normal faults across the gap. The absence of the Carbonate Rock units extending southwesterly from TW-2 is likely due to faulting of basement rocks upward along normal faults and down-cutting and erosion along an ancestral stream(s) in this deepest part of the gap.

Aquifer tests have been completed in the Alluvium, Carbonate Rock, and Older Alluvium units. GSSI (1995, 1999, and 2000) summarizes available aquifer test information, including aquifer testing they preformed as a part of the Cadiz Groundwater Storage and Dry-Year Supply Program. Additional aquifer tests were conducted as a part of this current study and described in detail in Appendix A. The aquifer test completed at TW-1, in the carbonate rock unit, demonstrates the highly permeable nature of this unit, which is consistent with significant dissolution and karstification of those carbonate rock units in the area. An aquifer test completed at TW-2 also demonstrates the highly transmissive nature of the Alluvial aquifer unit. TW-2 is completed in what is thought to be the axis of the deeper part of the Alluvial aquifer unit, which is likely the coarser part of the Alluvium unit. Table 4-7 summarizes aquifer test data for wells in the vicinity of the Fenner Gap.

4.2.2 Numerical Model Development

The Fenner Gap three-dimensional groundwater flow model described herein is based on the USGS MODFLOW-2000 numerical model. MODFLOW-2000 is a computer program that numerically solves the three-dimensional groundwater flow equation for a porous medium by using a finite-difference method (Harbaugh et al., 2000). MODFLOW-2000 is an enhancement to the previous MODFLOW numerical model originally documented by the USGS in 1984. MODFLOW-2000 requires that a conceptual model be developed of the groundwater system to be simulated, including, lateral and vertical extents of the system, definition of top and bottom of aquifers and confining units, boundary conditions (such as no-flow rock, specified inflows and outflows, constant heads where groundwater levels are maintained as constant, or some combination of these), hydrogeologic properties of aquifers, and observations to calibrate against (e.g., measured groundwater levels).

The purpose of the Fenner Gap groundwater flow model in this study is to assess whether it is likely that 30,000 AFY of groundwater is flowing through Fenner Gap, which is the expected long-term average recoverable water estimated to occur in the Fenner Watershed. Therefore, the numerical model is being used to test the hypothesis that 30,000 AFY is flowing through the gap. The model is used to solve the inverse problem, that is, given a boundary inflow of groundwater at the north end of the gap of 30,000 AFY, and measured steady-state groundwater levels, what distribution of aquifer properties (specifically hydraulic conductivity) is required to allow for this flow and is this distribution likely given available information on aquifer properties?

The conceptual model of the hydrogeology of the Fenner Gap described in Section 4.2.1 provides the basis for defining the lateral and vertical distribution of hydrogeologic units in the Fenner Gap and for use in mapping the distribution of these units in the numerical groundwater flow model.

Figure 4-38, a groundwater-level contour map, and historical groundwater-level data are used to define the lateral extents of the Fenner Gap groundwater flow model. Existing monitoring wells were surveyed for location and elevation and groundwater levels in wells were measured to obtain accurate groundwater levels in the gap. Table 4-8 shows survey results and groundwater levels for monitoring wells in the Fenner Gap, as obtained during this study. These groundwater levels, along with available groundwater-level data from the area, were used to construct the groundwater-level contour map shown in Figure 4-38. Historical groundwater-level data were reviewed to assess changes in groundwater levels in the area, in order to establish a steady-state groundwater-level condition through the Fenner Gap.

Figure 4-39 shows the lateral extents and grid selected for the Fenner Gap groundwater flow model. The lateral extents are defined by the 660-foot elevation groundwater contour on the north. This contour appears to be a stable groundwater level north of the Fenner Gap based on review of historical groundwater levels. The southern and western boundary is taken as a 590-foot elevation groundwater-level contour, that is a hybrid between the map presented in Figure 4-38 and a groundwater-level contour map provided by GSSI (1999). This hybrid map takes into account more recent survey data and historical groundwater levels that are possibly more representative of historical steady-state conditions. Given the distance of this boundary from Fenner Gap, the model simulations are not expected to be sensitive to the actual delineation of this boundary. Outcrops of bedrock (granitic rocks or unsaturated carbonate rocks) define the extents of the model on the northern and eastern boundaries of the model. Outside of these boundaries, the model assumes there is no groundwater flow (no-flow boundary) into or out of these no-flow areas.

The model grid is divided into square cells of 200 feet by 200 feet. Three layers are represented: Alluvial aquifer unit, Old Alluvium unit, and Carbonate Rock unit. PEST is used to estimate the hydraulic conductivity distribution of the Alluvial aquifer and Carbonate Rock units. The hydraulic conductivity of the Old Alluvium unit is set at 1×10^{-3} ft/d. The Carbonate Rock unit is represented as a single unit made up of variable rock types, as previously described. In actuality, those carbonate rocks are the principal water-transmitting units; however, for modeling purposes, these variable units are lumped together and average water transmitting properties are averaged in the model across the whole layer. Groundwater levels are simulated in the model at the center of each cell. This grid-cell resolution allows for good approximation of boundaries, both vertically and laterally, and for good resolution of variations in hydrogeologic properties and at the same time providing for reasonable simulation run times.

As indicated above, the purpose of the Fenner Gap groundwater flow model is to assess the likelihood that 30,000 AFY of groundwater is flowing through the gap. Therefore, the following boundary conditions are imposed on the north and west-southern boundaries. Groundwater levels along the 660-foot groundwater elevation contour are assumed to be constant at the 660-foot level. In addition, 30,000 AFY of groundwater inflow is assumed to occur through this boundary into the gap from Fenner Watershed, which is the long-term average annual recharge in the watershed, as previously described. Groundwater levels along the 590-foot groundwater-level contour are expected to be constant and steady at this 590-foot level. Also, there are no other sources of recharge or discharge within the Fenner Gap model domain area.

4.2.3 Application of PEST to Estimating Groundwater Flow through Fenner Gap

PEST is a model-independent parameter estimator (PEST) computer program that provides nonlinear parameter estimation for use with almost any numerical model. PEST has been widely used and extensively tested since 1994 by scientists and engineers all over the world working in many different fields, including biology, geophysics, geotechnical, mechanical, aeronautical and chemical engineering, ground and surface water hydrology and other fields (Doherty, 2004). PEST is often used in inverse modeling to aid in calibrating groundwater flow models. That is, PEST is used to estimate groundwater model parameter values, such as hydraulic conductivity, where measurements of groundwater levels and stresses (such as pumping or recharge) are known, so PEST calculates values of hydraulic conductivity that makes the groundwater flow model “calibrate” to the measured values. PEST makes many (often thousands) model-simulation runs to find the best set of parameter values that minimizes the residuals (differences) in simulated and observed measurements (e.g., groundwater levels).

PEST is used in the case of the Fenner Gap groundwater model to estimate hydraulic conductivity values of the Alluvial aquifer and Carbonate Rock units in the Fenner Gap given the following constraints (1) areal and vertical distribution of Alluvial and Carbonate Rock units as described above, (2) constant head values (groundwater elevations) of 660 feet and 590 feet on the northern and west-southern boundaries, respectively, (3) a target flux across the northern boundary of 30,000 AFY, (4) target groundwater-level measurements from monitoring wells in the Fenner Gap area based on recent groundwater levels, and (5) estimates of hydraulic conductivity from aquifer tests from previous studies and as a part of this study. These PEST-estimated hydraulic conductivity values are evaluated in the context of the hydrogeology of the gap, including available aquifer test data, to determine if these parameter estimates are reasonable. If these hydraulic conductivity values are considered reasonable, then it is reasonable that groundwater flow through the Fenner Gap is 30,000 AFY.

Regularization in combination with pilot points (Doherty, 2004) is used in the Fenner Gap groundwater flow model to estimate hydraulic conductivity value distributions in the Alluvial and Carbonate Rock unit aquifers. Regularization provides smoothing of parameter estimates, so that each grid cell is not considered to have a unique independent value and there is a smooth transition across the grid from high to low values. In addition, prior information is used to tell PEST the preferred values for each parameter and a range over which PEST may vary parameter values in order to match target values (i.e., measured groundwater levels). Parameter values are estimated by PEST at pilot points; then, kriging techniques are employed to spatially interpolate parameter values to all cells in the MODFLOW-2000 numerical finite-difference grid.

Figures 4-40 and 4-41 show the distribution of pilot points in Layer 1 (Alluvial aquifer unit) and Layer 3 (Carbonate Rock unit), respectively. Also shown are the target wells with water levels obtained from monitoring wells in the area (see Table 4-8).

Figures 4-42, 4-43, and 4-44 show simulated groundwater levels and target residuals, and hydraulic conductivity distributions for Layer 1 (Alluvial aquifer) and Layer 3 (Carbonate Rock unit), respectively, as determined from a PEST run. In this PEST run, hydraulic conductivity values of both the Alluvial aquifer and Carbonate Rock unit were bounded by a range between 1 to 600 ft/d. Groundwater levels and residuals (difference between measured groundwater levels and simulated groundwater levels) are posted at each monitoring well in Figure 4-42. The residuals are extremely low, indicating that the simulated groundwater levels are representative of measured groundwater levels.

Hydraulic conductivity values in the alluvial aquifer range from less than 20 to approximately 600 ft/d. The lowest values occur along the northern boundary, where the Alluvial aquifer is thickest. The Alluvial aquifer unit is represented as one layer in the model, when in actuality, it is likely several layers, with some layers having high hydraulic conductivity and other layers having lower values of hydraulic conductivity. The model-simulated values should be considered as vertically integrated averages of the true hydraulic conductivity. Again, these simulated values are those required to allow 30,000 AFY of groundwater flow into the gap area, assuming the granitic and metamorphic rock units form the base of the groundwater flow system in this area. PEST iterated to values of hydraulic conductivity close to those starting values, 110 ft/d provided as input at pilot points, in the western and southern areas of the model domain. The highest values of hydraulic conductivity, ranging to just over 600 ft/d are found in the east-central portion of the groundwater flow model. This part of the gap includes thinner alluvium and underlying carbonate units that vary greatly in thickness. PEST likely adjusts the alluvial hydraulic conductivity values in this area to accommodate groundwater flow across the gap. Regardless, the hydraulic conductivity values are within the range of values determined from aquifer tests in the alluvial aquifer, so these values are reasonable.

Hydraulic conductivity values in the carbonate rock unit aquifer range from less than 5 to approximately 600 ft/d. The highest values are located in the central portion of the model area. These values occur in the thinnest sections of alluvial and carbonate rock unit aquifers. PEST indicates that for 30,000 AFY of groundwater flow to occur through the gap, and to match observed groundwater levels, then average hydraulic conductivity values up to 600 ft/d are required in the Carbonate Rock unit aquifer, given the constraints on the Alluvial aquifer unit. Based on aquifer testing of the carbonate rock unit aquifer at TW-1 these values are reasonable.

Figures 4-45, 4-46, and 4-47 show simulated groundwater levels and target residuals, and hydraulic conductivity distributions for Layer 1 (Alluvial aquifer) and Layer 3 (Carbonate Rock unit), respectively, as determined from a second PEST run. In this PEST run, hydraulic conductivity values of both the Alluvial aquifer and Carbonate Rock unit were bounded by a range between 1 to 400 ft/d. Groundwater levels and residuals (difference between measured groundwater levels and simulated groundwater levels) are posted at each monitoring well in Figure 4-45. Again, residuals are low, indicating that the simulated groundwater levels are representative of measured groundwater levels.

Hydraulic conductivity values in the Alluvial aquifer range from less than 20 to approximately 400 ft/d. The lowest values occur along the northern boundary, where the Alluvial aquifer is thickest, similar to the previous PEST run. PEST iterated to values of hydraulic conductivity close to those starting values, 110 ft/d provided as input at pilot points, in the western and extreme southern areas of the model domain. The highest values of hydraulic conductivity, ranging to just over 400 ft/d are found in the central and eastern portion of the groundwater-flow model, which is larger than the extent of high conductivity values in the previous PEST run. PEST adjusts the alluvial hydraulic conductivity values in this area to accommodate groundwater flow across the gap. These hydraulic conductivity values are within the range of values determined from aquifer tests in the Alluvial aquifer, so these values are reasonable.

Hydraulic conductivity values in the carbonate rock unit aquifer range from less than 5 to approximately 400 ft/d. The highest values are located in the central portion of the model area. These values occur in the thinnest sections of alluvial and carbonate rock unit aquifers. PEST indicates that for 30,000 AFY of groundwater flow to occur through the gap, and to match observed groundwater levels, then average hydraulic conductivity values up to 400 ft/d are required in the Carbonate Rock unit aquifer, given the constraints on the Alluvial aquifer unit. Based on aquifer testing of the carbonate rock unit aquifer at TW-1 these values are reasonable.

Figure 4-48 shows a scatter plot of observed groundwater levels with simulated groundwater levels from the two PEST runs. This plot further demonstrates the good fit between the simulated and observed groundwater levels, i.e., the slope of the line is one to one. With 600 ft/d as the maximum hydraulic conductivity, the range of residuals was -0.27 to 0.19 feet, with a mean of -0.002 feet and a standard deviation of 0.10 feet. With 400 ft/d as the maximum hydraulic conductivity, the range of residuals was -0.52 to 0.62 feet, with a mean of -0.04 feet and a standard deviation of 0.34 feet. In addition, the residual standard deviation over the range is 0.008 and 0.026 for the first and second PEST runs, which are well within the 10 percent considered to be an industry standard.

The PEST results for hydraulic conductivity are considered possible sets of hydraulic conductivity values that can accommodate 30,000 AFY of groundwater flow through the Fenner Gap and match groundwater levels in monitoring wells and the range of hydraulic conductivity values observed from available aquifer tests.

4.2.4 Discussion of Groundwater Flow Model Results

The Fenner Gap groundwater flow model relies heavily on relatively high hydraulic conductivity values for the Carbonate Rock unit aquifer. Carbonate rock aquifers are not common in California, so there are not many examples to use for comparison and as a reality check on the groundwater flow model results; therefore, it is necessary to look outside the area for comparable hydrogeologic settings.

A carbonate rock aquifer that has been extensively studied and modeled is the Edwards aquifer in the San Antonio region of Texas. This aquifer is described as one of the most permeable and productive aquifers in the world (Lindgren, et al., 2004). Figure 4-49 shows hydrogeologic zones and catchment area of the Edwards aquifer from Lindgren (2004). The Edwards aquifer ranges to over 1,000 feet in thickness. Three types of permeability are recognized: matrix, fracture, and conduit. Matrix permeability is typically dwarfed by the fracture and conduit permeability and hydraulic conductivity and transmissivity vary over eight orders of magnitude and are multimodal.

Lindgren et al. (2004) and Painter et al. (2007) show the need to upscale hydraulic conductivity values from single-borehole tests. They have found that hydraulic conductivity values need to be increased substantially for use in numerical models, compared to those hydraulic conductivity values obtained from single-well tests. They found that geostatistical methods, such as kriging and cokriging during upscaling of hydraulic conductivity followed by Bayesian updating based on calibration to groundwater levels provided the best estimation of transmissivity and hydraulic conductivity values (Painter, 2007) for use in numerical groundwater flow models. Two component sets of hydraulic conductivity values are used in the Edwards aquifer model: a base component set and a conduit component set. The base component set of values of hydraulic conductivity simulated in a MODFLOW-2000 numerical groundwater flow model, using 0.25-mile grid spacings, of the Edwards aquifer range from less than or equal to 20 to 7,347 ft/d (Lindgren et al., 2004). The conduit component set ranges from 1,000 ft/d in the recharge area to as high as 300,000 ft/d in the confined portions of the aquifer and near spring discharge areas (Lindgren et al., 2004). Figure 4-50 shows the calibrated hydraulic conductivity distribution presented by Lindgren et al., (2004).

The carbonate rock units in Fenner Gap are not necessarily as permeable or productive as the Edwards aquifer; however, it may serve as a relatively representative analog for the Fenner Gap carbonate rock unit. Significant permeability, including the potential for conduit permeability, is evidenced by dissolution features in video logs of test wells, minimal drawdown during constant-rate aquifer tests and flattening of hydraulic gradients (as between MW-7 and MW-5). In addition, Mitchell Caverns itself demonstrates the occurrence of caverns in these Paleozoic carbonates in the area of study. Occurrence of highly permeable dissolution cavities and preferential pathways are expected to exist in the carbonate rock units underlying Fenner Gap. The hydraulic conductivity of these zones is expected to exceed hundreds of feet per day and perhaps approach thousands of feet per day, when upscaled to numerical model grid cells. So, hydraulic conductivity values simulated in the Fenner Gap model are considered reasonable estimates for the actual hydraulic conductivity values.

In total, data obtained from field investigations, INFIL3.0 watershed soil-moisture budget assessments, and Fenner Gap three-dimensional groundwater flow model simulations support a 32,000 AFY estimate of potentially recoverable water from the Fenner and northern Bristol Valley area. However, numerical models are based on simplified conceptual models of the more complex physical groundwater system and processes. Model construction and calibration results in nonunique models, which is demonstrated above in that two conceptual models (i.e., hydraulic conductivity distributions for Layers 1 and 3) provide a good fit to the observed data (groundwater levels and range of hydraulic conductivity values). The Fenner Gap models suggest a large area of highly transmissive alluvium and carbonate rock units, especially along the eastern side of the gap, extending into Bristol Valley. This area should be the focus of any additional field investigations as might be required for development of an operations plan and subsequent environmental impacts assessments, which also will provide further support of these potentially recoverable water estimates.

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Appendix A
Field Investigation Report (CD)