AB 303 GRANT
State of California Water Resources Department

GROUNDWATER MANAGEMENT IN THE INDIAN WELLS VALLEY BASIN
RIDGECREST, CALIFORNIA

June 2003

Prepared For:
EASTERN KERN COUNTY RESOURCES
CONSERVATION DISTRICT
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GROUNDWATER MANAGEMENT IN THE INDIAN WELLS VALLEY BASIN
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June 2003

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<tr>
<td>acre-ft/yr</td>
<td>Acre-feet per year</td>
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<tr>
<td>bgs</td>
<td>Below ground surface</td>
</tr>
<tr>
<td>BLM</td>
<td>Bureau of Land Management</td>
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<tr>
<td>CFC</td>
<td>Chlorofluorocarbon</td>
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<tr>
<td>EKCRCD</td>
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<tr>
<td>GIS</td>
<td>Geographic information system</td>
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<tr>
<td>IWVWD</td>
<td>Indian Wells Valley Water District</td>
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<tr>
<td>µg/L</td>
<td>Micrograms per liter</td>
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<tr>
<td>mg/L</td>
<td>Milligrams per liter</td>
</tr>
<tr>
<td>mybp</td>
<td>Million years before present</td>
</tr>
<tr>
<td>mgy</td>
<td>Million gallons per year</td>
</tr>
<tr>
<td>MK</td>
<td>Morrison Knudsen Corporation</td>
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<tr>
<td>mph</td>
<td>Miles per hour</td>
</tr>
<tr>
<td>msl</td>
<td>Mean sea level</td>
</tr>
<tr>
<td>NAWS</td>
<td>Naval Air Weapons Station</td>
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<tr>
<td>TDS</td>
<td>Total dissolved solids</td>
</tr>
<tr>
<td>TtEMI</td>
<td>Tetra Tech EM Inc.</td>
</tr>
<tr>
<td>USBR</td>
<td>U.S. Bureau of Reclamation</td>
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<tr>
<td>WGI</td>
<td>Washington Group International, Inc.</td>
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<tr>
<td>ybp</td>
<td>Years before present</td>
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EXECUTIVE SUMMARY

The Eastern Kern County Resource Conservation District received a Local Groundwater Assistance Fund Grant (AB 303) on behalf of the Indian Wells Valley Cooperative Groundwater Management Group. The purpose of the grant is to conduct groundwater studies or to carry out groundwater monitoring and management activities in accordance with the groundwater management authority of the voluntary and cooperative Groundwater Management Plan of the Indian Wells Valley Cooperative Groundwater Management Group. Members of the Indian Wells Valley Cooperative Groundwater Management Group include the Eastern Kern County Resource Conservation District, Naval Air Weapons Station (NAWS) China Lake, Indian Wells Valley Water District, Kern County Water Agency, City of Ridgecrest, Bureau of Land Management, Inyokern Community Services District, Indian Wells Valley Airport District, IMC Global Inc., and Quist Farms.

This report summarizes the work conducted under the AB 303 grant, including (1) a summary and interpretation of the available data that were collected, (2) a hydrogeologic conceptual model, (3) identification of gaps in the available data, and (4) recommendations for future work, studies and/or research projects. The primary objective of this effort is to better understand the hydrodynamics, groundwater chemistry, and groundwater availability within the Indian Wells Valley groundwater basin.

Hydrogeologic Conceptual Model

Based on a review of geologic, hydrologic, and groundwater quality data, the hydrogeologic conceptual model for the Indian Wells Valley has been refined. A recognition that the Pleistocene sedimentary depositional history has resulted in the current hydrogeologic constraints within the valley underlies the basis of the current model. Key elements of this emerging hydrogeologic conceptual model are reflected by the recognition of younger recharge along the Sierra Nevada front from both surface and some fracture flow. Shallow groundwaters of the valley floor are consistently of Holocene (less than 10,000 years before present) age. The ages obtained for the deeper waters of the regional aquifer are generally between 10,000 and 40,000 years before present. A few deeper samples reflect slightly younger ages than would be expected from the stratigraphic depths at which the samples were collected. This likely is a result of younger recharge into these zones.

The regional aquifer is primarily composed of coarse sands and gravels with some thin interbedded lacustrine clays. Groundwater within the regional aquifer may occur under confined, semiconfined, or unconfined conditions. Where the thick lacustrine clays are present, groundwater is semiconfined to
confined. Groundwater conditions become unconfined where these clays pinch out. In general, the regional aquifer is unconfined in the vicinity of Inyokern and in the western- and southernmost portions of Ridgecrest, including the Southwest and Intermediate Well Field areas. In the eastern portion of the valley, the regional aquifer is confined or semiconfined by lenses of the lacustrine and playa deposits. Water quality is very good for most wells completed in the regional aquifer. Concentrations of total dissolved solids range between 200 and 600 milligrams per liter near the water supply wells for the Indian Wells Valley and increase to the north and east of this region.

**Groundwater Usability**

Groundwater is the sole source of potable water supply in the Indian Wells Valley and is used by the Indian Wells Valley Water District, Inyokern Community Services District, NAWS China Lake, IMC Global Inc., private drinking water well owners, and agricultural concerns. In 2001, the largest producers of groundwater in the Indian Wells Valley were the Indian Wells Valley Water District (with production of approximately 8,393 acre-feet per year or 2,735 million gallons per year), private agricultural users (with production of 7,942 acre-feet per year or 2,500 million gallons per year), NAWS China Lake (with production of 2,839 acre-feet per year or 925 million gallons per year), and IMC Global Inc. (with production of approximately 2,700 acre-feet per year or 880 million gallons per year).

Pumping of water supply wells has resulted in a pumping depression in the Intermediate Well Field area, which could result in poorer quality water being drawn in from the north and east. Stable isotope ratios calculated for groundwater samples collected from wells screened in the regional aquifer plot close to the global meteoric water line, indicating that little evaporation occurred prior to recharge. Old, isotopically light groundwater represents Pleistocene recharge that infiltrated under cooler climatic conditions and/or at higher elevations. A few wells completed in the deeper portion of the regional aquifer indicate the potential for poorer quality waters at depth. Drawdown in the regional aquifer is occurring at a rate of 1 to 1.5 feet per year, particularly in the eastern two-thirds of the Indian Wells Valley groundwater basin, and the possibility therefore exists of drawing poorer quality waters from the eastern portion of the basin or deeper zones. The development of groundwater resources in areas southwest of the Intermediate Well Field area should lessen the likelihood of drawing in the poorer quality water.

Projected total groundwater production in the Indian Wells Valley has been estimated by analyzing recent (past 5 years) production trends for each individual producer and assessing this rate of increase along with other available data, such as demographic information. Producers with the greatest projected increases in water use are the Indian Wells Valley Water District and small residential producers that are projected to
increase production at an average annual rate of 2 percent and 1 percent, respectively, through the year 2020. Total agricultural use and groundwater use by IMC Global Inc. are both projected to increase annually by about 0.01 percent. The Inyokern Community Services District and NAWS China Lake are each projected to experience decreases in annual groundwater production of 0.05 percent per year. The estimated combined effect on projected total annual groundwater production in the Indian Wells Valley is a net annual increase of 0.09 percent. This translates to an estimated increase in Indian Wells Valley total production from 21,400 acre-feet per year (6,780 million gallons per year) in 2002 to 22,867 acre-feet per year (7,453 million gallons per year) in 2020.

Data Gaps

Considerable information is available concerning water use within the valley and general water chemistry. Significant information regarding groundwater flow and mixing zones has been gained through age dating and isotope studies. However, several critical data gaps have been identified, and it is therefore recommended that additional information be collected to perform the following:

- **Expand the coverage of monitoring points, particularly in the western portion of the valley.** More data points are needed in the western portion of the valley to better refine and quantify our understanding of the significance of recharge entering the western margins of the valley from the Sierra Nevada and to quantify the safe yield of the groundwater basin.

- **Quantify water level fluctuations and hydraulic properties.** A considerable amount of historical data are already available; however, additional data are necessary to develop a transient hydrologic budget that is defined according to both the effects of groundwater pumping from multiple sources across the basin, as well as the storage capacity and resultant safe yield of the aquifer.

- **Quantify flow between water-bearing zones and groundwater basins.** Additional isotope and age-dating investigations should be conducted to determine the amount of groundwater mixing between hydrogeologic zones and to further define the potential for interflow between groundwater basins, such as the Rose Valley to the north, Salt Wells Valley to the east, Red Rock Canyon basin to the south, and Sierra Nevada to the west.

- **Quantify storage capacity and safe yield.** New field measurements are needed that can be combined with previously collected data to quantify the storage capacity and safe yield of the regional aquifer through numerical calculations.

- **Quantify watershed recharge.** Various recharge studies have been conducted within the Indian Wells Valley and the associated estimates of recharge amounts obtained from them vary widely. Recharge estimates can be refined through additional monitoring along the western margin of the basin, including direct measurements in the Sierra Nevada drainages and additional groundwater age-dating.

- **Determine applicability and effects of the Arsenic Rule.** The January 21, 2001, Arsenic Rule requires that water systems reevaluate their current master planning to include arsenic treatment
that would bring levels down from the previous arsenic concentration standard of 50 micrograms per liter to the new standard of 10 micrograms per liter, achieving compliance by 2006. Samples collected from wells screened in the regional aquifer, as part of the Navy’s basewide study, indicate naturally occurring arsenic concentrations that range from 5 to 62 micrograms per liter. Water purveyors need to consider whether it is more cost effective to treat the water to reduce arsenic or to apply for an exemption. Under the Safe Drinking Water Act, the U.S. Environmental Protection Agency will consider exemption to the Arsenic Rule if the following four criteria apply: (1) the public water system is unable to achieve compliance; (2) the system has no reasonable alternative source of drinking water available; (3) the exemption will not result in an unreasonable risk to health; and (4) the system cannot reasonably make management or restructuring changes that would result in compliance or improve the quality of drinking water if compliance cannot be achieved. The Indian Wells Valley Cooperative Groundwater Management Group should collectively review both treatment and exemption options and develop a plan for implementation.

- **Develop cooperative groundwater monitoring and water survey reports.** A Groundwater Monitoring Plan was developed previously by the Kern County Water Agency with review and input by the Indian Wells Valley Cooperative Groundwater Management Group. This plan should be reviewed, revised, and updated to address the data gaps identified in this report. Similarly, groundwater survey reports should be prepared on an annual basis as a cooperative group effort to (1) identify groundwater use and production within the community; (2) present groundwater elevation, flow direction, and water quality data from the monitoring well network established in the Groundwater Monitoring Plan; (3) develop or update hydrographs generated from water level and pressure transducer data; and (4) discuss general water use and water quality trends within the Indian Wells Valley groundwater basin.

The hydrogeologic conceptual model presented in this report will continue to be refined and quantified as these data gaps are resolved and new information is received. Target areas for which additional information is necessary are primarily located in the western portion of the valley, including the southwest, west central, northwest, and Sierra Nevada canyons. The following methods or investigations are recommended to fill one or several data gaps:

- Add information from new monitoring or production wells as the data become available basinwide.
- Install pressure transducers to collect continuous water level and temperature measurements.
- Install canyon monitoring stations that are equipped with a weather station, recording stream gage, soil moisture monitoring system, and one or more piezometers.
- Conduct aquifer performance tests and install new test wells, piezometers, or velocity sensors in the southwest portion of the basin.
- Conduct pilot tests to determine the feasibility of groundwater injection or blending.
- Sample selected monitoring wells in the western portion of the basin and Intermediate Well Field area for inorganic and general chemistry parameters and target isotopes.
Recommendations for Groundwater Planning and Management

Included in this report are several approaches for resolving these data gaps along with a range of anticipated costs. Recommendations are also provided for cooperative planning and management of the groundwater resource. These recommendations are as follows:

- Schedule annual updates of geographic information system data, water quality data, documents, and references to be added to the Indian Wells Valley Cooperative Groundwater Management Group website (www.iwvgroundwater.org).

- Develop cooperative groundwater monitoring plans and comprehensive water surveys that combine data collected by all members of the Indian Wells Valley Cooperative Groundwater Management Group.

- Limit large-scale pumping in areas significantly impacted by declining water levels and water quality and expand into less developed portions of the Indian Wells Valley.

- Blend groundwater containing low concentrations of total dissolved solids with groundwater containing higher concentrations. Consider prior treatment of a portion of the poorer quality water before blending.

- Recycle water through the use of gray water for irrigation, industrial processes, or other established avenues.

- Evaluate importation of water and possible underground injection during the winter months to augment production during the peak summer season.
1.0 INTRODUCTION

The Eastern Kern County Resource Conservation District (EKCRCD) applied for, and subsequently received, a Local Groundwater Assistance Fund Grant (AB 303) on behalf of the Indian Wells Valley Cooperative Groundwater Management Group. The purpose of the grant is to conduct groundwater studies or to carry out groundwater monitoring and management activities in accordance with the groundwater management authority of the voluntary and cooperative Groundwater Management Plan of the Indian Wells Valley Cooperative Groundwater Management Group. Members of the Indian Wells Valley Cooperative Groundwater Management Group include the EKCRCD, Naval Air Weapons Station (NAWS) China Lake, Indian Wells Valley Water District (IWVWD), Kern County Water Agency, City of Ridgecrest, Bureau of Land Management (BLM), Inyokern Community Services District, Indian Wells Valley Airport District, IMC Global Inc., and Quist Farms. The authorization for this organization is found in the California Water Code, Sections 10750 and 10750.4.

The study conducted under the scope of the AB 303 grant and presented in this document focuses on the groundwater resources and hydrostratigraphic conditions in the Indian Wells Valley, which is located approximately 150 miles north of Los Angeles (Figure 1-1). The Indian Wells Valley is in the southwestern corner of the Great Basin section of the Basin and Range Physiographic Province. The province is characterized by isolated, north-trending mountain ranges separated by desert basins, with the Indian Wells Valley being the most western of these desert basins.

1.1 PURPOSE AND OBJECTIVE

The purpose of this study is to provide an updated hydrogeologic conceptual model that can be used as a groundwater management tool for future groundwater development and management activities. (The definition of a hydrogeologic conceptual model as it pertains to this document is provided in Appendix A, which is a glossary of terms used in this report.) The primary objective of this study is to develop a technically and legally defensible framework of groundwater management and planning tools that will incorporate existing and new information in a cooperative planning effort between local agencies and water producers. Components of the study include the following tasks:

- **Task 1.** Purchase computers and programs to generate data and geographic information system (GIS) map products.
- **Task 2.** Develop a database that formalizes and standardizes the data.
• **Task 3.** Update the hydrogeologic conceptual model (documented in this report).

• **Task 4.** Develop a GIS that would also assist with the implementation of the groundwater management plan.

• **Task 5.** Develop the Indian Wells Valley Cooperative Groundwater Management Group website ([www.ivwgroundwater.org](http://www.ivwgroundwater.org)), where GIS coverages, references, and documents can be accessed by the public.

• **Task 6.** Develop a framework of groundwater management tools.

Specifically, this report is intended to establish a baseline and provide a more complete understanding of the relationships among groundwater level changes, groundwater flow directions and gradients, and supply well pumping effects. Groundwater chemistry data are also reviewed and evaluated to determine notable trends and changes in water quality and age relative to groundwater movement. The hydrogeologic conceptual model developed as part of this evaluation is intended to enable a better understanding of groundwater dynamics in the Indian Wells Valley groundwater basin (Figure 1-2).

1.2 **SCOPE**

The scope of this study is to provide an updated hydrogeologic conceptual model of the Indian Wells Valley groundwater basin. Hydrogeologic conceptual models are powerful planning tools that integrate what is already known about a groundwater basin and help identify data gaps that must be addressed to make resource management decisions. Hydrogeologic conceptual models are revised as new information is obtained and integrated into the understanding of site conditions. Previous versions of the hydrogeologic conceptual model for the Indian Wells Valley groundwater basin identified specific groundwater flow paths, hydraulic interconnections between water-bearing units, areas of potential recharge and discharge, and the hydraulic properties of the individual geologic units (Kunkel and Chase 1969; Dutcher and Moyle 1973; Erskine 1989; Berenbrock and Martin 1991; U.S. Bureau of Reclamation [USBR] 1993; Houghton HydroGeo-Logic 1996; St. Amand 1986). The updated hydrogeologic conceptual model presented in this report is based on both historical and new data (1992-2003) that are publicly available and used as a baseline starting point. This conceptual model is therefore dynamic and should be refined as additional data become available. The following tasks were conducted under the scope of the AB 303 grant with regard to updating the model:

• **Data Assessment/Data Compilation.** A comprehensive review of all water quantity and water quality data for areas within and adjacent to the Indian Wells Valley, California, was performed. Historical data for the Indian Wells Valley were entered into the existing database utilized by the Kern County Water Agency as part of the review. All new data were consistent with existing
water quality and water production data. An in-depth review of the universe of all known extant wells in Indian Wells Valley resulted in the selection of a reliable well subset used to measure groundwater levels. The National Imagery and Mapping Agency surveyed key wells under the Navy’s direction. Data gaps were also identified as part of the review.

- **Hydrogeologic Data Review and Interpretation.** A detailed conceptual model of the Indian Wells Valley groundwater basin was developed. The conceptual model is based on all data collected during past studies by entities associated with the Indian Wells Valley Cooperative Groundwater Management Group. The hydrogeologic conceptual model provides insight to the nature, character, and extent of the aquifer and includes (1) aquifer boundaries and areal extent, (2) estimates of aquifer permeability and connectivity of hydrogeologic zones, (3) water quality characteristics, and (4) effects of water use on the regional aquifer. Data limitations and the nature and significance of data gaps were also assessed.

- **Preparation of Final Report.** This report summarizes and interprets the available data that were collected, presents the hydrogeologic conceptual model, identifies gaps in the available data, and provides recommendations for future work, studies and/or research projects.

Data included in this document have been gathered from published reports and databases provided by NAWS China Lake, the Kern County Water Agency, the Kern County Council of Governments, the IWVWD, and the City of Ridgecrest. In addition, the Navy and IWVWD are providing water supply and production data so that water use patterns and corresponding influences on groundwater levels can be incorporated into the hydrogeologic conceptual model. Additionally, an improved and more detailed understanding of the basin and regional tectonic framework has been incorporated into the model.

### 1.3 LIMITATIONS

The data evaluations and analyses that form the basis for the hydrogeologic conceptual model presented in this document are based upon existing data that are publicly available. One component of the data assessment/data compilation task was to determine, out of the universe of available data, how much of the data are useable. The following criteria were considered in the analysis of data and water well usability:

- Is the information readily available?
- Are data point coordinates (x, y, and z) known or can they be readily obtained?
- Are well construction, completion, and lithologic information readily available?
- Are the integrity and status of the well known?
- Is there an available water level/water quality sampling port?
- If the well is used for production, is there a known production schedule?
• Are historical data available? Can water levels and water quality data be collected currently or in the future?

• What is currently known about the horizontal and vertical components of the conceptual hydrogeologic model? What are the groundwater basin boundary conditions?

• What is currently known about natural and artificial sources of recharge, discharge, and changes in storage?

• What geophysical data, maps, and aerial photographs are available?

The wells selected for use in this study have National Imagery and Mapping Agency coordinated, reliable construction information (particularly regarding the screen intervals), and are completed in the regional aquifer. Based upon this initial data screening, the data set was refined and the hydrogeologic conceptual model was updated accordingly. Data gaps are identified throughout this document, particularly in Sections 3.5 (related to geology and hydrogeology) and 4.4 (related to water quality and geochemistry). In addition, Section 6.2 summarizes the significant data gaps that should be filled to refine and modify the conceptual model. These data gaps are then prioritized according to the following two factors: (1) how critical are the data to the overall needs and objectives of the program and (2) how realistic is it to fill the data gap from a logistics and cost-benefit standpoint. Following the assessment of significant data gaps, Section 6.3 provides recommendations for groundwater planning and management to strategically manage development of the hydrogeologic conceptual model and groundwater management plan. Furthermore, it should be noted that the hydrogeologic conceptual model and groundwater management plan are dynamic and should be modified and updated as existing data gaps identified in this report are filled.
2.0 BACKGROUND

Located within the Southern Lahontan Hydrologic Region, the Indian Wells Valley groundwater basin has a surface area of approximately 600 square miles (380,000 acres) and is bounded by the Sierra Nevada on the west, the Coso Range on the north, the Argus Range on the east, and the El Paso Mountains and the Spangler Hills on the south (Figure 1-2). Ridgecrest is the only incorporated community in the Indian Wells Valley. Most of the land surrounding Ridgecrest and the unincorporated community of Inyokern is federally owned and administered by the Navy at NAWS China Lake or by the BLM under the California Desert Conservation Area Plan. Land use in the Indian Wells Valley also includes urban and rural residential areas, agricultural holdings, and commercial enterprise.

2.1 TOPOGRAPHY

The Indian Wells Valley is characterized by the topography of the Basin and Range Physiographic Province. The province is characterized by isolated, north-trending mountain ranges separated by desert basins. The Indian Wells Valley is the most western of these desert basins and is bordered on the west by the southern Sierra Nevada, on the east by the Argus Range, and on the south by the El Paso Mountains and the Spangler Hills. On the north, the valley is partially separated from the Coso Basin by the White Hills. The Garlock fault is the southern boundary of the area and separates this province from the Mojave Desert on the south.

Broad alluvial fans extend into the Indian Wells Valley from Sierra Nevada canyons and the Argus Range, forming bajadas several miles wide. The bajadas slope into the east-central portion of the valley, where several playas are located. Smaller alluvial fans extend into the basin from the south and east. The largest of the playas is China Lake. Other playas in the valley include Mirror Lake and Satellite Lake, which are normally dry. Elevations in the Indian Wells Valley vary from about 2,150 feet above mean sea level (msl) at the China Lake playa to about 2,790 feet msl at the southern margins of the study area (Figure 1-2). The Indian Wells Valley watershed contains about 860 square miles, about 500 square miles in the mountains and hills and about 360 square miles in the valley.

2.2 CLIMATE

The climate in the Indian Wells Valley is semiarid as the result of a rain shadow created by the Sierra Nevada. Average annual precipitation within the Indian Wells Valley watershed varies from 5 to 10
inches per year, falling at the rate of less than 5 inches per year in the Ridgecrest/China Lake area, up to about 5 inches per year in the El Paso Mountains to the south, up to about 6 inches per year in the Argus Range to the east and the Coso Range to the north, and up to about 10 inches per year in the Sierra Nevada to the west (IWVWD 2002). Monthly average temperature and precipitation data are provided on Figure 2-1. Most of the precipitation occurs between October and March, with January being the wettest month. Typical desert thunderstorms occur in the late summer. Precipitation falls in the form of rain, with the exception of occasional snow at the higher mountain elevations during the winter months. Climatological records gathered from NAWS Range Meteorology indicate a cumulative total of 4.61 inches of precipitation during 2001, with the most significant rainfall event occurring on February 13 with a measured rainfall of 0.80 inch (Figure 2-2).

Temperatures in the Indian Wells Valley often exceed 100 °F during the summer months (the longest spell on record is 85 consecutive days, from June 17 through September 9, 1994) and average about 55 °F during the winter months (IWVWD 2002). In 2001, the mean daily minimum and the mean daily maximum were 49 °F and 81 °F, respectively, with an average daily range of 32 °F. The average daily temperatures ranged from a low of 37.6 °F on February 13, 2001, to a high of 95.6 °F on July 3, 2001 (Figure 2-2). Prevailing winds in the valley are from the southwest, and the average daily wind speed for 2001 was 3.7 miles per hour (mph). However, wind speeds in excess of 25 mph have been recorded throughout the year, and winds speeds in excess of 50 mph are common between October and June (California Department of Water Resources 1978).

2.3 DEMOGRAPHICS

Ridgecrest’s incorporated area includes approximately 13,300 acres. According to U.S. Census Bureau data for 2000, Ridgecrest’s total population was 24,927 and Inyokern had a total population of 984. Ridgecrest acts as the urban center for northeastern Kern, southern Inyo, and northern San Bernardino Counties. NAWS China Lake supplies a limited amount of base housing. The average housing occupancy is 2.5 persons per dwelling unit.

The IWVWD is the primary purveyor of public water supplies in the Indian Wells Valley. Their projections for population growth in their service area are an increase from approximately 27,000 in 2000 to approximately 34,100 by 2020 (IWVWD 2002). This population estimate is based on U.S. Census
data for 1990, assuming the water district’s population is distributed as follows: 100% of Census Tract 402, 60% of Census Tract 403, and 20% of Census Tract 401.

2.4 LAND USE

The Indian Wells Valley groundwater basin occupies land within Kern, San Bernardino, and Inyo Counties. Most of the land is federally managed by NAWS China Lake and the BLM. A generalized land use map is shown on Figure 2-3. The largest land use is for the NAWS China Lake North Range. NAWS China Lake’s mission is to be the Navy's full-spectrum research, development, test, and evaluation and in-service engineering center for weapons systems associated with air warfare (except anti-submarine warfare systems), missiles, missile sub-systems and aircraft weapons integration, and assigned airborne electronic warfare systems, as well as to operate and maintain its air, land, and sea ranges. China Lake has a workforce of approximately 3,000 civilian employees and 350 military personnel and is supported by over 1,300 contractor employees (NAWS Public Affairs Office 2002).

Ridgecrest is contiguous with the southern boundary of NAWS China Lake, while Inyokern lies to the southwest of the installation. These urban communities provide housing, retail and light industrial services, and recreational opportunities for the local population. The remainder of the Indian Wells Valley is a predominantly rural area surrounded by wilderness, parks, forests, open space, and conservation areas. The Los Angeles Department of Water and Power aqueduct system runs near the western margin of the study area in the foothills of the southern Sierra Nevada. The U.S. Forest Service has jurisdiction over the Inyo National Forest along the western boundary.

Inyo County is in the northern portion of the basin. Unincorporated rural communities in the northwestern portion of the study area along Highway 395 include Pearsonville, Little Lake, and Coso Junction. Pearsonville, located in the Indian Wells Valley groundwater basin, is a rural community at the Inyo/Kern County boundary and is designated for industrial, commercial, and residential land uses. Little Lake is a rural community with a commercial land use designation. Coso Junction, in Rose Valley, is designated for public land use because of its proximity to, and association with, a Caltrans rest area. The Inyo County General Plan identifies land use designations for all land in the county (Inyo County 2001). The general plan was formally updated in November 2001; no land uses were changed during the plan’s revision, and established land use patterns are not expected to change in the foreseeable future.
The Kern County General Plan (Kern County 1994) identifies land use guidelines and designations for all land in the county and contains a Desert Region section for land use management in the eastern portion of the county. Eastern Kern County is a rural area made up predominantly of federal lands intermixed with private lands. Ridgecrest and Inyokern are located in the Desert Region of Kern County. Land use in Ridgecrest is designated as a mixture of residential, commercial, institutional, and recreational uses. The Ridgecrest General Plan (City of Ridgecrest 1994) calls for the city to continue as a support community for NAWS China Lake. Established land use patterns for the City of Ridgecrest are not expected to change in the foreseeable future. Inyokern’s economic base consists primarily of service-oriented establishments located along State Highway 178. The Inyokern Airport services Ridgecrest, Inyokern, and the surrounding area. Approximately 22 percent of Inyokern’s land use is industrial (Navy 1997). Most of the remainder of Kern County land uses are low-density residential or open space. Land uses in the eastern portion of Kern County are expected to remain the same or be similar to established use patterns in future years.

The southeastern portion of the study area is in the Mountain-Desert Planning area of San Bernardino County. Most of the land is designated for open space and conservation use and is managed by the Ridgecrest Field Office of BLM’s California Desert District. The land is managed for multiple uses, including grazing, mining, wilderness, and recreation. The San Bernardino County Plan (San Bernardino County 2000) identifies land use guidelines.
3.0 HYDROGEOLOGIC SETTING

3.1 GEOLOGY

The following discussion presents the most current understanding and interpretation of the geology of the Indian Wells Valley area. A detailed understanding of the geologic setting is a prerequisite to developing the hydrogeologic conceptual model. As defined in this document, the Indian Wells Valley groundwater basin boundary includes the southwestern El Paso Basin and the Coso Basin north of NAWS China Lake, both of which drain into the Indian Wells Valley.

The Indian Wells Valley is the westernmost basin in the southwest corner of the Great Basin section of the Basin and Range Physiographic Province and is also considered to be at the boundary of the Basin and Range and the Mojave Desert in east central California (Figure 3-1). As with most Basin and Range alluvial basin settings, the Indian Wells Valley is typified by a structural basin partially or entirely surrounded by Tertiary or older rocks. The surrounding highlands are often tectonically active and centers for high heat flow and volcanic activity. The erosion of the highlands is the source of the depositional valley fill. This fill is the principal groundwater aquifer in the Indian Wells Valley. The Indian Wells Valley is best described as a half-graben feature (Monastero and others 2002) that is the result of both extensional and transtensional Late Cenozoic tectonics, having received thick sedimentary depositional valley fill throughout this time (see Figure 3-2). The Indian Wells Valley has received sediments since at least the Miocene (Monastero and others 2001), and Pleistocene deposition was predominantly controlled by major pluvial episodes. The Indian Wells Valley was periodically linked to the Owens River drainage during the Pleistocene. The basin is one of the most seismically active in California.

Extensive geologic studies have been conducted in two basins fed by the ancestral Owens River and bounding the Indian Wells Valley, namely Searles Lake (Smith and Street-Perrott 1983; Smith and others 1983; Smith 1979) and Owens Lake (Smith and others 1997). These studies have documented Pleistocene episodic depositional events along this drainage. The intensive studies of the Searles Lake basin were conducted due to the extensive and economically significant evaporite deposits, whereas the more recent detailed studies of the Owens Lake basin were primarily focused at Pleistocene paleoclimatic research.
The Indian Wells Valley has been studied in previous investigations primarily focused at better understanding the groundwater in the area (Moyle 1963; Kunkel and Chase 1969; St. Amand 1986; Berenbrock and Martin 1991; USBR 1993; Berenbrock and Schroeder 1994; Tetra Tech EM Inc. [TtEMI] 2003). The Indian Wells Valley Groundwater Project (USBR 1993) resulted in the drilling of ten deep monitoring wells to depths of up to 2,000 feet. The tectonic history of the Indian Wells Valley has also been of significant interest (Von Huene 1960; Zbur 1963), while neotectonic surface features were mapped by Roquemore (1981) as well as Roquemore and Zellmer (1987). More recently, the Indian Wells Valley was the focus of four deep borings and geophysical studies sponsored by the Navy’s Geothermal Program Office (Monastero and others 2002). In addition, several hundred shallow (<300 feet) borings and groundwater monitoring wells have been completed during environmental restoration activities at NAWS China Lake since 1984 (TtEMI 2003), and the data provide detailed insight into the shallow stratigraphy of the area.

During the Navy’s basewide hydrogeologic characterization project, sediment and rock cores were collected from 26 soil borings that were drilled in the Indian Wells Valley, 17 borings in the Salt Wells Valley, and 4 borings in the Randsburg Wash Area in up to 1000+ feet of Quaternary sediments. These exploratory borings were used to guide monitoring well placement in the Indian Wells Valley and the Salt Wells Valley; 16 wells were completed in the Indian Wells Valley and 9 wells were installed in the Salt Wells Valley. Several hundred boring logs from water wells, previous exploratory borings, and the Navy’s Installation Restoration Program wells and borings were also used to assess groundwater conditions. Some of these new well logs were more detailed than those from previous efforts due to extensive core recovery and detailing lithologic logging. A limited set of laboratory and isotopic carbon analyses were performed for some exploratory borehole soil samples. The Navy’s recent basewide study (TtEMI 2003) should be considered a detailed reconnaissance to provide standardization, consistency, and a more complete interpretation of the basinwide depositional history of the sediments as they relate to the current and past groundwater conditions. Sufficient detail was achieved to provide an improved understanding of the Quaternary history of the study area. These previous studies provided the basis and framework for the conceptual hydrogeologic model of the Indian Wells Valley as summarized in the report of the basewide study (TtEMI 2003). Appendix B of the basewide study summary report contains descriptions with interpretations of the study’s boring logs and geophysical logs.
3.1.1 Physiographic and Geologic Setting

The Indian Wells Valley is bordered on the west by the southern end of the Sierra Nevada, on the east by the Argus Range, and on the south by the El Paso Mountains and the Spangler Hills, which are in turn bounded on the south by the Garlock fault (Figure 3-1). On the north, the main valley is separated from the Coso Basin by a low ridge called the White Hills and from the Coso Range as well as Coso volcanic fields by uplifted lacustrine outcrops and several Quaternary basalt flows. The Coso Basin dry wash drains through Airport Lake and into the Indian Wells Valley from the north. In the northwest, stream flow from Rose Valley continues today, albeit at a fraction of the past pluvial input of the Owens River. The Indian Wells Valley is nearly equidimensional (19x22 miles), an anomaly for the central Basin and Range valleys (Monastero and others 2002). The Salt Wells Valley is located southeast of the Indian Wells Valley, is topographically lower than the Indian Wells Valley, and forms an extension of the Searles Lake Valley drainage. A series of ridges expose the crystalline basement complex of the southern Argus Range, including a prominent knoll known as Lone Butte separating the Indian Wells Valley and the Salt Wells Valley.

The stratigraphic units in the vicinity of the Indian Wells Valley range in age from Paleozoic to Quaternary (Figure 3-2). An uplifted plutonic and metamorphic Mesozoic granitic basement complex underlies these basins. The Sierra Nevada batholiths and the associated low-angle frontal fault bound the western edge of the Indian Wells Valley. Structurally, the Indian Wells Valley is a half-graben formed by down-to-the-east movement on the Sierra Nevada frontal fault (Monastero and others 2001). Over 7,000 feet of valley fill sediments are present in the western portion of the valley, but the average depth of basin fill sediments is approximately 2,000 feet. These basin fill sediments include the Paleogene Goler Formation and the Miocene Ricardo Group, which consists of the Cudahy Camp Formation and Dove Springs Formation that filled Indian Wells Valley from the south (Cox 1982; Loomis and Burbank 1988). Tertiary continental sedimentary and volcanic deposits make up the majority of the fill, which ranges from about 1,000 to approximately 7,000 feet thick. Miocene to Quaternary volcanics also crop out on the perimeter of the Indian Wells Valley basin and, in a few places, flow into the valley.

Several seismic reflection lines and four deep exploration holes drilled near these lines over the past decade by the Navy's Geothermal Program Office (Monastero and others 2001) have refined the earlier observations made by Kunkel and Chase (1969) and Zbur (1963). The earlier investigations noted that outcrops of older lacustrine deposits were present in the White Hills and partially covered by Pleistocene basalts in the northern portion of the Indian Wells Valley. They also mapped an older lacustrine outcrop
in the southeast portion of the Indian Wells Valley in the present housing area of NAWS China Lake. This area will be discussed further below. Monastero and others (2002) have described this syntectonic basin fill as the White Hills sequence. In the western portion of the Indian Wells Valley it is over 4,500 feet thick. The seismic survey data and borehole evidence indicate that the first 900 feet of the sequence that overlies the basement consists of debris flow and slump deposits originating from the rapid rise of the Sierra Nevada along low-angle normal faults near the western basin margin. Alluvial fan deposits dominate the overlying 3,400 feet of the section. In the central Indian Wells Valley, the White Hills sequence is over 3,000 feet thick and overlies the Miocene Dove Springs Formation, and likely the older Goler Formation where present. These older Miocene formations appear to be missing in the western Indian Wells Valley (Monastero and others 2001), which may indicate they were not deposited or have been eroded. The central section of the sequence has predominantly sand-shale sections characteristic of fluvial or lacustrine deposition. A basalt encountered at about 3,200 feet below ground surface (bgs) is dated at 3.9 million years before present (mybp). Above the basalt, claystone and silty sandstone with some thin limestone indicates a fluvial-lacustrine depositional environment. In the subsurface in the eastern Indian Wells Valley, the White Hills sequence appears to be dominated by fluvial, fan, and fan-delta sequences.

Overlying the White Hills sequence are the unnamed Pleistocene (post 2 mybp) and Holocene (post 10,000 years ago [Recent]) deposits. The Pleistocene deposits in the basin consist primarily of fan, alluvial, deltaic, and thick lacustrine deposits (Figure 3-3). Holocene sedimentation in most of the valley has been minor compared to sediment deposition rates that occurred during the previous wet Pleistocene climate, but where deposition has occurred, it is dominated by sand and gravel deposited in steep alluvial fans emerging into the basin as gentle alluvial plains and the broad thin Owens River delta plain. These alluvial plains have been the source of silt and clay that have been redeposited in several low dune-playa complexes throughout the Indian Wells Valley. The present China Lake playa is the largest in the Indian Wells Valley.

Holocene deposits typically range from a few feet thick in the area surrounding the China Lake playa to over 200 feet of alluvial fan deposits overlying the first-encountered lacustrine sediments of late Pleistocene age along the margins of the basin (see discussion of borings TTIWV-SB01, -SB03, -SB07, and -SB10 in Appendix B of the basewide study summary report [TtEMI 2003]). Much of the Holocene deposition has been removed by eolation in many areas of the China Lake playa. The unnamed Pleistocene deposits are estimated to be from 1,200 to 1,800 feet thick in the western and central portions of the Indian Wells Valley to less than 300 feet thick along the eastern margin of the valley. This
estimate is primarily based on the 2,000-foot deep USBR (1993) wells, three deep Geothermal Program Office borings and seismic reflection data (Monastero and others 2002), and estimated sedimentation rates established in Owens Lake (Smith and others 1997) and Searles Lake (Smith and others 1983, 1997).

The four areas noted below are marginal to the central portion of the Indian Wells Valley but are relevant to the understanding of the hydrogeology of the Indian Wells Valley and are described further. The southwestern, western, and Coso Wash areas are within the groundwater basin. The Salt Wells Valley is the primary downgradient basin from the Indian Wells Valley.

- **Southwestern Indian Wells Valley.** The southwestern portion of the Indian Wells Valley narrows into a sub-basin dominated by the northeast trending drainage of Little Dixie Wash with its two major tributaries, Freeman Wash and Sage Wash. The surface topography is composed of older and younger alluvium, as well as fluvial fill along the washes. The southern terminus of the Sierra Nevada bounds the basin on the northwest with the El Paso Mountains and Black Hills on the southeast. Much of this current basin is known as the El Paso Basin, a localized depositional basin that along with the Indian Wells Valley has received sediments from southern sources for over 20 million years. Little is known of the deep stratigraphy or structure of this basin but presumably the Goler, Cudahy Camp, and Dove Springs (Ricardo) Formations make up a significant portion of the infilling here. Based on borehole cuttings from wells USBR-1 and USBR-2, there is at least 1,800 feet of alluvial fan deposition in the basin. Reportedly, cuttings from the bottom 400 feet in USBR-1 were identified as the Ricardo Formation. Two Navy exploratory borings and wells drilled in 1998 and 2001 southeast of Freeman Junction also penetrated brown alluvium to 765 feet. Zbur’s (1963) seismic refraction survey suggests that the depth to the crystalline bedrock is about 2,500 feet near the mouth of the basin. At the northeast opening of this sub-basin, a drop of over 500 feet into the broader Indian Wells Valley suggests that the basin is on a significant upthrown bench created by a splay of the Sierra Nevada frontal fault. The Ricardo Formation outcrops along the complete length of the southern boundary of the basin, suggesting significant downward displacement of the Ricardo below the basin. Groundwater investigations in the basin have been limited.

- **Coso Wash.** The Coso Wash or Coso Basin is a northern topographic extension of the Indian Wells Valley. The Coso Wash is bounded on the west by the Coso volcanic field and on the north by the Coso Range. To the east, it is bordered by the normal-faulted Wild Horse Mesa volcanics and the Argus Range. The Coso Wash’s southern dry drainage to the Indian Wells Valley is constrained by the 460-foot high White Hills anticline. The Airport Lake playa forms along the northern boundary of the White Hills and is the Coso Basin’s topographic low before dropping into the Indian Wells Valley. The Indian Wells Valley fault trace of the Airport Lake fault splits into the northwest trending Little Lake fault and continues northward into a series of splays across the White Hills and in a left stepping fashion along the western margin of the Coso Basin (Unruh and others 2002). The Coso Basin appears to have formed as a pull-apart half-graben that occurred sometime after 3.5 mybp (Monastero and others 2002). The Navy’s Geothermal Program Office recently drilled five test holes in the upper Coso Basin. The Coso Range to the west of this basin is a major source of geothermal power. Two deep wells were completed to 7,000 to 10,000 feet in the upper wash. The borings indicate that the alluvial sand
and conglomerate fill is about 1,800 feet deep, with a 500-foot thick basalt flow encountered at 550 feet bgs. The underlying granite is in several discreet blocks, faulted and fractured (Bjornstad and others 2001). These findings provide further evidence that this extensional basin evolved more recently than the Indian Wells Valley half-graben extension and that deposition of the sediment and basalt basin fill has kept pace with the growing basin.

While extension and valley expansion has slowed in the Indian Wells Valley, the Coso Wash and Coso Range have active crustal extensional tectonics still unfolding (Unruh and others 2002). This active extensional terrain has been formed by crustal stretching and thinning, resulting in a significant thermal increase and magma bodies below this region. The groundwater in the basin has not been investigated.

- **Western Indian Wells Valley.** The Indian Wells Valley is bounded on the west by the steep frontal slopes of the Sierra Nevada. The low-angle frontal fault roughly defines the Sierra Jurassic to Cretaceous granites and the alluvial fan facies that make up the western flank of the Indian Wells Valley. Above and flanking some of the fan facies in the northwest portion of the valley are outcrops of the older alluvium (Kunkel and Chase 1969), which are characterized as debris flow and as mega breccias by Monastero and others (2002). Fifteen major canyons drain the eastern Sierra Nevada slopes, forming fans and providing the most significant surface runoff into the internal drainage of the valley. Significant subsurface flow from the adjacent fractured bedrock is suggested by several investigators (Thyne and others 1999; Austin 1987). This fan facies appears to be 400 to 600 or more feet thick in the northwest corner (monitoring wells USBR-10, USBR-6, NR-1). The frontal fans transitioned into fan-delta or delta depositional environments as they prograded into a lake that occupied a sag pond throughout much of the Pleistocene. This sag represents the deepest portion of the Indian Wells Valley sedimentary basin and has been characterized as a gravity low by Monastero and others (2002) using information from seismic reflection surveys and deep borings SNORT 1 and 2. This Sierra Nevada margin sag appears to have formed as a consequence of the low-angle extensional normal (listric) faulting that created the Indian Wells Valley half-graben. This half-graben was filled in with the highland headwall debris and slump as the Sierra Nevada uplifted and the valley dropped. As Indian Wells Valley continued to grow due to the extensional tectonics, the sag became underfilled with deposits of coarse alluvial debris, allowing a persistent lake to develop for at least 2 million years. As the Sierra Nevada uplift decreased, extension slowed, and transtensional tectonic movement took over, Sierra glacial meltwater also decreased and alluvial fan deposition returned as the lake disappeared. South of Leliter Road, the subsurface lacustrine environment quickly disappears near Bowman Road. To the east of the sag are sediments representing deltaic package sequences. The ancestral Owens River drained into the Indian Wells Valley from the north through Rose Valley into the Little Lake narrows created by Pleistocene basalt flows. A delta formed in the northwestern Indian Wells Valley northeast of the deep sag from the ancestral Owens River and the thick deposition appears to have been accommodated in the basin by a sizable down-dropped section of the basin between the Little Lake fault zone and the Airport Lake fault zone (TtEMI 2003).
Salt Wells Valley. Except for a 20-foot rise, the Indian Wells Valley surface drainage is almost connected to the Salt Wells Valley through a low ancestral drainage east of Knox Road that runs through the NAWS Magazine Bunker storage area (TtEMI 2003). Groundwater flow exiting the Indian Wells Valley through this low as fracture flow has been speculated by Kunkel and Chase (1969). Topographically the Salt Wells Valley is connected with the Searles Lake Basin through Poison Canyon. On the flanks of the Salt Wells Valley, the Quaternary stratigraphy is generally alluvial fan and fluvial veneer over older weathered crystalline bedrock (Figure 3-1). In the subsurface below the present upper Salt Wells Valley wash drainage and under the extensive mud flat, there is evidence of lacustrine mud and clays. In some areas, such as in the vicinity of the Navy’s Salt Wells Propulsion Plant, a thin lacustrine sediment veneer is intercalated with several sandy fan units containing gravel and cobbles. Significant tufa deposits and towers are aligned along both Pleistocene lake high stands and lineaments perpendicular to the strand lines. Diatomite beds of over 10 feet in thickness crop out along the western margin of the upper Salt Wells Valley drainage. The single hydrologic zone was characterized during the Navy’s basewide study (TtEMI 2003).

3.1.2 Stratigraphic History

For at least the last 2 million years, the Indian Wells Valley has been the site of persistent lacustrine sedimentation. The most recent (late Pleistocene) lakes have left evidence of their presence, including thick depositional sequences of silt and clay, as well as strand lines (beaches), beach rock, tufa deposits, and lake outlets. The Pleistocene China Lake is part of a complex chain of lakes fed by the interconnecting Owens River on the eastern edge of the Sierra Nevada that extends from the Mono Basin to Death Valley (Pleistocene Lake Manly) (Figure 3-4) (Smith and Street-Perrott 1983; Grayson 1993). During wetter and cooler times, these pluvial lakes and rivers were fed by runoff from significantly increased precipitation. Cooler temperatures slowed evaporation of the lakes as Sierra Nevada glacial advances filled the rivers and lakes with fine rock flour, reducing overall biological productivity (Benson and others 1996).

The heaviest flow in the Owens River took place during periods of Sierra Nevada glacial advance, with increased precipitation providing runoff. Cooler, wetter winters and summers increased flow-through, but also significantly delayed Sierra Nevada snowpack melt, maintaining more constant flow through the summer. River flow continued during the drier and warmer interglacial periods when the glaciers melted and retreated, but at much reduced levels. Higher evaporation during the interglacial periods lowered the lake levels.

During the wet intervals and interglacial melts, large quantities of sediment-laden water drained into the Owens River drainage, feeding the chain of pluvial lakes (Figure 3-4). The five large pluvial lakes
(Owens, China, Searles, Panamint, Manly) were intermittently interconnected by the Pleistocene Owens River. In glacial China Lake, the river lost much of the sediment load and formed a large delta in the Indian Wells Valley basin. China Lake filled and reached a depth of 40 to 70 feet during the late Pleistocene. The most recent glacial lake overflowed through an outlet at an elevation of approximately 2,190 feet msl (Dutcher and Moyle 1973) north of Lone Butte into the Salt Wells Valley, down through Poison Canyon, and on into Searles Lake (Figure 3-1). The previous outlet had been located in the dry gap at about 2,420 feet msl east of Ridgecrest now occupied by Highway 178. This sill may have undergone compressional uplift throughout the late Pleistocene, thus finally cutting off the flow to the Salt Wells Valley at this higher elevation and redirecting as well as downcutting to about 2,180 feet msl the outlet through the Magazine Area drainage. Such tectonic compression is apparent in the southern Indian Wells Valley (Monastero and others 2002).

The first two lakes, Owens Lake and China Lake, were vast settling ponds for the sediment-laden Owens River (Smith and Pratt 1957). Searles and Panamint Lakes, being downstream, became progressively enriched in soluble salts, as evaporation from each preceding basin concentrated the solutes in the residual water. Monomineralic salt layers accumulated in these downstream basins where they are now preserved as thick subsurface saline mineral deposits (Smith 1979).

China Lake coalesced with Searles Lake during high water stands, and the Salt Wells Valley alternated between being an embayment to Searles Lake and a narrows between the two lakes. The Pleistocene depositional history of the Indian Wells Valley and the ancestral China Lake is more closely linked to the Owens Lake outfall. U.S. Geological Survey investigators (Smith and Pratt 1957; Smith and others 1997; Benson and others 1996) have compiled high-resolution records of the late Pleistocene climate history in Owens Lake, which is important to understanding the history of sedimentation in China Lake. Based on isotopic oxygen ratios and analyses of total inorganic carbon, Smith and Benson’s teams concluded that Owens Lake overflowed intermittently throughout the glacial period spanning 52,500 to 15,000 years before present (ybp). They concluded, among other things that the fine-grained detrital material in the Owens Lake sediments is predominately rock flour that settled out from the glacial melt waters. The results of the study identified 19 glacial cycles, each lasting about 1,500 years, during the glacial period from 52,500 to 23,500 ybp.

From 22,400 to 12,000 ybp, the most recent glacial advances and retreats occurred more frequently (less than 1,000 years per cycle) until about 12,500 ybp, when the cycles were terminated by a severe drought. Bischoff and Cummings (2001) studied glacial rock flour from the Owens Lake cores and found that the
abundance of rock flour in the sediment was proportional to the glacial advances in the Sierra Nevada. Smith (1979, 1987) provides a history of the Searles Lake fluctuations, which also presumably reflect the outflow history of China Lake. The dates obtained during the Navy’s basewide study confirm a late Pleistocene age for the uppermost clay sections in the Navy borings and provide an initial framework for a more complete late Pleistocene timeline in the Indian Wells Valley (Figure 3-5 and Table 3-1) (Couch and others 2003).

The lacustrine stratigraphy is generally identifiable in a discrete sequence or package that conforms to the classic regressive lacustrine upward-coarsening section of Picard and High (1981). Postulated lake levels in the Indian Wells Valley and the Salt Wells Valley were also instructive and used to predict the extent of the most recent Pleistocene lakes. The evidence for these strand lines is aligned with the known outlets (TtEMI 2003). In the Indian Wells Valley, these levels roughly follow the 2,200-, 2,300-, and 2,400-foot topographic contours, while in the Salt Wells Valley the contour alignment of the tufa towers strongly supports Kunkel and Chase’s 2,260-foot strand line. Both lithologic evidence from the borehole stratigraphy and radiocarbon dating of samples from 11 key boreholes support these postulated shorelines (Figure 3-6).

3.1.3 Tectonic Setting

The active tectonic and structural regional history of the last 2 million years in the Indian Wells Valley has been dominated by transtensional dextral faulting that likely began in the late Pliocene. The Indian Wells Valley is bounded by older normal faults, the Sierra Nevada fault on the west and the Argus fault on the east. The formation of the Indian Wells Valley half-graben likely began in the early Pliocene with the uplift of the low-angle Sierra Nevada and subsidence of the Indian Wells Valley, with as much as 3 kilometers of subsidence realized. The modern structural setting is marked by at least three sets of northwest-southeast trending dextral strike-slip fault zones that cut across the Indian Wells Valley.

According to Monastero and others (2001) and Walker and Glazner (1999), Basin and Range extension followed by the transtensional shear (Eastern California Shear Zone) is part of the ongoing evolution of the North American and Pacific plate dynamics. The transtensional shear features are seen in both the Coso Range-Coso Wash and the Indian Wells Valley and are part of several regional-scale accommodations along these plate boundaries. The Mojave Desert region south of the study area has both active transcurrent faulting (Garfunkle 1974) as well as transpressional movement (Bartley and others 1990). The three active and related faults in the Indian Wells Valley reflect this history. The northwest-southeast trending Little Lake fault (TtEMI 2003, Figure 2-1) reflects predominantly transtensional dextral shear with a normal-slip component, while the north-south trending Airport Lake
fault and Argus frontal fault zone exhibit mostly normal slip movement (Roquemore 1983). Recent examination of these faults suggests that they are part of the same single regional tectonic stress regime. The Sierra Nevada uplift appears to act as a uniform microplate that is moving rigidly towards the northwest at a rate of 13 to 14 millimeters per year. The Sierra Nevada uplift and the Basin and Range extension have given way to microplate transtension over the last 2 million years (Glazner and Unruh 2001). Deep seismic reflection data (Figure 3-7) clearly resolve the subsurface flower structures of these fault zones, with some of the fault traces having recent surface expression (Monastero and others 2002).

In the Indian Wells Valley, the earlier extensional tectonic and structural history controlled the depositional style and stratigraphic history that was altered by the Pleistocene transtensional dynamics. The center of depositional fill has moved from west to east within the last few hundred thousand years.

The Salt Wells Valley is a topographic low formed by splays of the Argus frontal fault crossing the southern terminus of the uplifted Argus Range. This fault trace has been eroded and the valley cut into the uplift of the Argus Mesozoic complex platform, which separates the Indian Wells Valley graben from the Searles Valley syncline (Smith 1991).

3.1.4 Depositional Environments

Four basic facies assemblages are identified in the Quaternary syntectonic basin fill: fan, fluvial-alluvial-deltaic, lacustrine, and isolated evaporitic sequences. Additional surface and near-surface deposits include eolian, playa, and calcareous carbonate deposits. The first three facies occur throughout the Indian Wells Valley. Thick evaporites appear to be rare in these basins and are the product of special depositional circumstances. Eolian and playa assemblages are common but limited to the present depocenters of each basin. The predominant surface and near-surface calcium carbonate deposits can generally be related to Pleistocene lakeshore and water table interfaces.

Fan Facies

Alluvial fan facies consisting of heterogeneous, lenticular beds of unconsolidated clay, silt, sand, gravel, and boulders emanate from the larger drainages of the mountain ranges surrounding Indian Wells Valley, especially the Sierra Nevada and the Argus Range. Thick fans dominate the southern flank of the Indian Wells Valley and thin fan and alluvial sheets veneer the Salt Wells Valley crystalline bedrock and thin lacustrine facies and margins. The deposits are characterized by an abundance of locally derived, well graded boulders, gravel, and sand that is often referred to as fanglomerate. Mudflows consisting of a heterogeneous mixture of all grain sizes are locally common. Ephemeral transportation of coarse debris...
from the surrounding mountains occurs primarily during times of sheet flooding or cloudbursts in the present climate. Highly permeable channel deposits often cut down through older deposits that include low permeability mudflows, creating zones with highly variable permeability. The present surface slope of these deposits usually exceeds 100 feet per mile (Kunkel and Chase 1969).

During past pluvial events, and to a lesser extent today in the present hydrologic regime, lenses of coarse-grained fan deposits have had an important local effect by channeling groundwater flow into the basin. The fan deposits constitute the principal pathway by which runoff from the surrounding mountains recharges the groundwater reservoir (Bean 1989). However, individual beds in fan deposits are the least laterally continuous of the Quaternary deposits due to the cut-and-fill and localized lobate sheet-like nature of the deposition. Fan deposits have originated from most of the mountain fronts surrounding the Indian Wells Valley and the Salt Wells Valley. The majority of the fan deposits within the valleys have coalesced, and the distal fan toes have merged to form broad alluvial aprons (bajadas). These fan deposits can roughly be grouped by age into young, intermediate, and old following the criteria outlined by Christenson and Purcell (1985). Young deposits are from 0 to 15,000 years old; intermediate age deposits cover a broader range at 15,000 to 700,000 years, encompassing the late to middle Pleistocene, and old fan deposits are older than 700,000 years, spreading across the early Pleistocene and late Tertiary.

The surface fans and subsurface fan deposits to about 800 feet bgs beneath the Indian Wells Valley and the Salt Wells Valley are mostly in the intermediate age group. Older fans are common in the deeper subsurface and much older representatives are found in the White Hills sequence of Monastero and others (2002). During pluvial lake high stands during periods of significant runoff, these intermediate age fans were fan-deltaic when the fan prograded into the lake. The distal fan-delta facies sediments are better-sorted, finer sands, often with graded bedding and fewer channel deposits, but frequently interbedded with lacustrine fines. Darker gray and olive hues are indicative of deposition in the reducing subaqueous lake environment.
Fluvial-Alluvial-Deltaic Facies

The alluvium of the study basins consists principally of lenticular beds of unconsolidated clay, silt, sand, and gravel derived from the Sierra Nevada and surrounding mountain ranges. The slope of the present alluvial topographic surface is generally less than 50 feet per mile. The composition of the alluvium reflects the bedrock of the primary source area. The sands are arkosic in nature, and generally angular. Alluvium that is encountered at depths greater than about 200 feet bgs is referred to as the “older alluvium” by Kunkel and Chase (1969). The alluvium consists primarily of fluvial sediments deposited in distributary braided stream channels and broad sheets and in inter-channel areas. The alluvium is generally a continuum of the gradual fan aprons descending into basins.

During the wet, high-runoff periods of the Pleistocene, drainage from the Owens River entered from the northwest into the Indian Wells Valley, flowed along the Sierra Nevada front south from Owens Valley, and formed a broad shallow lake. The river dropped its sediment load to form a broad, nearly flat, and relatively thin alluvial plain. As the basin filled, a broad but thin delta formed. Accommodation of the delta fill was enhanced by downwarp tectonics above the Airport Lake and Little Lake fault zones (Monastero and others 2002, Seismic Section IWV 92-02, SP 1300-1350).

The stratigraphy of the deltaic sediments in the Indian Wells Valley is complicated by the incursions of interfingering flanking fan and alluvial deposits on the margin of the delta. These alluvial deposits frequently advanced basinward from the surrounding elevated terrain. The prograding low alluvial fan sheet deposits (from bottom) that protrude into the lacustrine environment are essentially sediments of the prodelta environment. These alternating transgressive and regressive conditions are recorded throughout the basin’s sedimentary record.

The lake’s regressive facies can be considered a baseline condition, as feeding alluvial stream and delta deposits constantly tended to fill the lake so that the shoreline sands encroached onto the fine lake floor muds. However, transgressive overlap was superimposed on this sequence as the alluvial fans and apron sediments were carried further into the valley. The rise and fall of the lake further imposed alternating transgressive and regressive conditions (Lahee 1961). Minor unconformities are common and represent lake level drops as well as erosion from lake advances. During arid interglacial periods when the source area was tectonically inactive, the stream discharge and coarse clastic sediment load generally decreased, while deposition of silt and clay still predominated (Kunkel and Chase 1969). Weakly developed soil was likely common on some of the exposed sediments revealed by the receding lake waters. As lake levels rose, wave base reworked these soils, and therefore they were poorly preserved. Tectonic
accommodation appears to have been relatively uniform during the Pleistocene, keeping pace with the Owens River sediment delivery and confining the major delta depositional sequence in the northeast quadrant of the Indian Wells Valley.

**Lacustrine Facies**

The lacustrine facies consists of thick lenticular to semicontinuous horizons of predominantly micaceous silt and silty clay to plastic clays with occasional fine sandy horizons. Many of these horizons are laminated muds, often varve-like, and indicative of suspension settling in quiet water. Some of the clays are likely authigenic. Some of these sediments typically contain freshwater ostracods, diatoms, gastropods and mollusc shells, although clean, highly plastic clays are not unusual. The dark-colored lacustrine clay deposits represent the anoxic bottom muds of the Pleistocene lake and sometimes include thin horizons of impure limestones (marls), and some calcareous sandstone and conglomerate. These deposits are widespread below the younger alluvium throughout the Indian Wells Valley and are encountered below 150 feet in most borings in the central Indian Wells Valley. In the western Indian Wells Valley, along the Sierra Nevada front where the graben is the deepest, thick lacustrine sediments begin at a depth of about 350 feet and are over 1,000 feet thick. The few exposed outcrops of lacustrine deposits are deformed and indurated, suggesting that they are “older” Pleistocene sediments. They are present at the surface and at relatively shallow depths east of the NAWS China Lake main gate at the intersection of Halsey and Nimitz Avenues (Kunkel and Chase 1969), on the east side of the Argus Range, and near Coso Lake. South of the wastewater treatment impoundments and north of the golf course, isolated surface mounds of lacustrine silt have survived late Pleistocene and Holocene erosion. Crossbedded and ripple-marked calcareous sandstones on the south shoreline of Mirror Lake represent beach rock from the last lingering Pleistocene lake.

An example of this lacustrine horizon is the greenish gray clay that starts at about 90 feet bgs beneath Armitage Field, at about 45 to 90 feet bgs beneath Michelson Laboratory, and at about 100 to 150 feet bgs beneath the SNORT Road Landfill. This lacustrine zone is over 800 feet thick in boring TGCH-1, located east of Armitage Field. Borings TTIWV-SB23 and USGS MD-1 in the middle of the China Lake playa indicate fine-grained clay-rich lacustrine deposits to at least 700 feet bgs (Smith and Pratt 1957). Recent seismic reflection traces reveal that interbedded low-permeability silts and clays beginning at depths ranging from about 50 to 150 feet bgs extend to the southwest for at least 2.5 miles along Inyokern Road. In the western Indian Wells Valley, the clays are over 1,500 feet thick along the Sierra Nevada front.

**Eolian, Playa, and Calcium Carbonate Deposits**
Holocene surficial deposits include playa and eolian deposits in addition to the fan, alluvial, fan-delta and lacustrine deposits described above. Additionally, secondary calcium carbonate on surface or near-surface exposures in the alluvial fill and fan deposits is also common. The China Lake playa generally has alkali surface crusts and a shallow depth to groundwater. Except for standing water from a recent rainfall and surface drainage, the water present at China Lake is due to surface and shallow groundwater saturation, occasional groundwater discharge, and upward capillary movement. In contrast to the China Lake playa, North Dry (Paxton Ranch), Mirror, Satellite, Coso, Airport, and Searles Lakes (playas) are rarely wet except when occasionally covered by recent rainwater and drainage to the playas. The China Lake playa is characterized as a discharge playa, whereas playas like Satellite and Airport Lakes, which generally retain a hard, relatively smooth surface and where the groundwater is at some depth, are considered recharge playas (Rosen 1994). When dry, the flat surface of both playa types is continuously eroded and deflated. Thick evaporites or salt deposits have not been identified in the Indian Wells Valley playa surface or subsurface deposits. Some leakage from this system probably occurs via subsurface fracture flow through the crystalline bedrock on the east side of the main playa. The thick clay-rich lacustrine sediments underlying the China Lake playa limit downward migration of both surface water and shallow groundwater. First-encountered groundwater in the China Lake playa area is characterized by high concentrations of total dissolved solids (TDS). Water quality in the deep waters below the playa has not been characterized. An attempt to install a well deeper than 1,000 feet at Navy boring location TTIWV-SB23, located at the southwestern end of the China Lake playa, met with strongly artesian conditions at 736 feet and loss of the boring. The effort did reveal the considerable confining pressures under the clays of the central basin.

The playa deposits interfinger with the surrounding Holocene alluvium in the Indian Wells Valley. The distinction between the present playa deposits and underlying lacustrine deposits is generally not evident. West of the China Lake playa, eolian sand has been deposited by the prevailing westerly winds as interplaya dunes and dune fields. The origin of these sands appears to be the desiccated Pleistocene Owens River outwash delta plain. To the east of China Lake, the deflated playa surface fines extend well into the Salt Wells Valley where loess over 50 feet thick is not uncommon. Stabilized dunes are found east of Mirror Lake. The Holocene eolian sand and silt deposits are generally less than 30 feet thick and unsaturated (Kunkel and Chase 1969) across the majority of the basin. These near-surface deposits veneer much of the valley and across the playas on windward slopes of the Argus Range. These deposits are often interbedded with alluvial deposits and occasionally have incipient soils developed on the older eolian horizons. Eolated bedrock is found along the eastern Indian Wells Valley bedrock exposures about 20 to 60 feet above the playa surface. Radiocarbon dates determined during the basewide study and also
by Davis (1978) for the near-surface sediments of the playa suggest a dearth of younger Holocene sediments, indicating loss by deflation or nondeposition.

Black organic-rich soils are fairly common in the borings fringing the ancestral lakes. On the margins of the China Lake playa, at depths of 10 to 25 feet, a thick sequence of black organic clays suggests that during Holocene time, extensive thickly vegetated swamps likely surrounded the intermittent and shallow China Lake on its south shore (St. Amand 1986). Mastodon or mammoth tusks found at the surface in this area support the contention that this was likely a heavily vegetated area (TtEMI 2003). Since these large mammals became extinct around 8,000 to 10,000 years ago, these deposits are certainly at least as old as very early Holocene (Illinois State Museum 1995). Davis (1978) reports a radiocarbon date of 18,000 +/- 4,500 ybp for some mammoth ivory collected about 6 miles west of this location.

Although not strictly of Holocene age, an accumulation of secondary calcium carbonate or caliche in the alluvial fill and fan deposits is found throughout the NAWS China Lake area. In some cases, these soil carbonate deposits are better termed calisols since they meet the definition of a paleosol (Mack and others 1993; Bronger and Catt 1989). The calcium carbonate may occur as interstitial filling in unconsolidated sediments or as a surface coating on the clastic components of these sediments. Cementation by calcium carbonate alters the chemical and physical properties of the original sedimentary fill. This process binds clasts and grains into larger particles or cemented horizons, decreasing porosity in these carbonate horizons (Wells and Schultz 1980). Most calisol horizons and outcroppings are found in the near-surface and are Holocene or late Pleistocene in age, although calcium carbonate at depth in older fan deposits is not uncommon and is generally related to old soil horizons (Bull 1972; Gile and Hawly 1972). Several general types of carbonate deposits, which have been labeled informally as caliche, have been noted in this area and are typical of the Basin and Range Physiographic Province Quaternary features (Hunt 1974). These include cemented vadose lenses, pedogenic capillary fringe cementation, tufa crust deposits and towers, and lakeshore beach rock.

**Evaporite Deposits**

Only minor evaporite deposits have been found in the Indian Wells Valley basin. The China Lake playa contains surface efflorescent silty crusts of sodium chloride. Traces of phosphates, nitrates, borates (ulexite), and sulfates (gypsum) are common (Austin and others 1983). Gypsum (selenite) is common in the silty clays of the low mounds of surviving lake sediments from the last Pleistocene lake (10,070 +/- 155 ybp) found on the margins of the current playa.
Calcite and aragonite are found both in the near-surface playa sediments as well as at depth in the lacustrine deposits. These minerals are not diagnostic for evaporite formations. However, scattered subsurface carbonate evaporite minerals like gaylussite have been reported at depth in the lacustrine/playa sediments (TtEMI 2003; Smith and Pratt 1957). This mineral is more likely indicative of geochemistry of at least moderate salinity, although not a closed highly evaporative lake (Smith and Haines 1964). No significant subsurface accumulations of the traditional saline evaporite sequences that precipitate in restricted lake environments (Eugster and Hardie 1978) were encountered in any of the Navy borings or other historical drilling efforts in the Indian Wells Valley or the Salt Wells Valley.

One exception was the finding of a 20-foot thick opal-sepiolite clay facies at 238 feet bgs in northeastern Indian Wells Valley, southeast of the White Hills (TtEMI 2003). This mineralogy is interpreted as forming from the silica-rich and high pH waters of a closed lake environment. The restricted lake formed in a tectonic sag, likely a small sub-basin formed by downdrop from faulting subparallel to the Airport Lake-Argus frontal fault trend along the margin of the larger Indian Wells Valley lake. The water flowing into the basin may have been from the upstream geothermal source areas. This appears to have been a relatively isolated environment and is not expected to be laterally extensive outside of the sub-basin.

### 3.2 HYDROGEOLOGY

Previous investigators have described the hydrogeology of the Indian Wells Valley in terms of a shallow and a deep aquifer (Kunkel and Chase 1969; Dutcher and Moyle 1973; Berenbrock and Martin 1991). According to their definition, the shallow aquifer occurs in the eastern portion of the valley and includes most of the young lacustrine deposits and shallow alluvium where underlain by lacustrine deposits. During the 1990s and early 2000s, significantly more exploratory drilling and well installations were conducted in the Indian Wells Valley groundwater basin. These investigative projects included:

- **Indian Wells Valley Groundwater Project.** This project involved a cooperative effort among the USBR, IWVWD, North American Chemical Company (now known as IMC Global Inc.), and NAWS China Lake. The primary objective of this project was to refine estimates of the life of the natural groundwater resource in the valley and to identify management concepts to conserve and extend the useful life of the valley’s groundwater resources (USBR 1993). Ten monitoring wells were drilled to a maximum depth of 2,000 feet to provide additional data in the southwest, west, and northwest areas.

- **Background Groundwater Chemistry Study, NAWS China Lake.** An evaluation of shallow water quality data for groundwater samples collected over four consecutive quarters (November 1998 through August 1999) from 17 monitoring wells screened in the shallow hydrogeologic
zone within the main China Lake Complex at NAWS China Lake was conducted as part of this study. The objective of this study was to develop a validated, defensible background data set for naturally occurring, inorganic constituents in shallow groundwater beneath the NAWS China Lake facility in the Indian Wells Valley to be used in Installation Restoration Program site-to-background statistical comparisons within the China Lake Complex (TtEMI 2001).

- **Fence Line Groundwater Monitoring Study, NAWS China Lake.** The original intent of this investigation was to evaluate groundwater flow and the potential for contaminant transport along portions of the property boundary (fence line) between the China Lake Complex and the City of Ridgecrest, California. In 1999, seven new monitoring wells and ten groundwater velocity sensors were installed and water quality and hydrologic (water level and velocity) monitoring was conducted along the fence line and in the vicinity of the City of Ridgecrest sewage treatment ponds. The results of the 1999 groundwater monitoring indicated that there is no contaminated groundwater moving off base from the southern boundary of the China Lake Complex to the City of Ridgecrest. All subsequent fence line groundwater monitoring efforts have been limited to groundwater level and velocity monitoring in an expanded monitoring well network of on- and off-base monitoring and production wells to characterize groundwater flow within an approximately 80-square mile area in the central portion of the Indian Wells Valley (TtEMI and Morrison Knudsen [MK] 2000b; TtEMI and Washington Group International, Inc. [WGI] 2001; TtEMI in press).

- **Basewide Hydrogeologic Characterization of NAWS China Lake.** The objective of this project was to gain a better understanding of the hydrogeology across NAWS China Lake, encompassing three separate basins: the Indian Wells Valley, Salt Wells Valley, and Randsburg Wash. The four-year investigation (TtEMI 2003) included drilling and continuously coring 23 exploratory soil borings up to a maximum depth of 1,036 feet, measuring water levels in almost 200 wells, collecting and analyzing water samples from 52 locations for isotopes and intrinsic tracers, installing 25 additional monitoring wells (depths of the wells ranged up to 988 feet), and determining background water quality, oxygen/deuterium, and carbon-14 ($^{14}$C) parameters. Slug tests were also conducted in the 25 newly installed wells.

Based upon these more recent investigations, the vertical division of two main aquifers, one shallow and the other deep, has been more recently described in terms of hydrogeologic zones – shallow, intermediate, and deep. It should be noted that “hydrogeologic zones” may be saturated or unsaturated, or a combination of both. As a result, the term “hydrogeologic zone” has been adopted to account for the localized heterogeneities that result throughout the Indian Wells Valley groundwater basin. For the purposes of this document, two groundwater units are discussed - the saturated portion of the shallow hydrogeologic zone and the regional aquifer (including the saturated portions of the intermediate and deep hydrogeologic zones). Each of these groundwater systems is discussed in greater detail below.
3.2.1 Shallow Hydrogeologic Zone

The shallow groundwater system has been studied extensively by the Navy to better understand water movement under sites where potential contamination may have occurred. Groundwater within the shallow hydrogeologic zone is generally limited to the eastern and northern portions of the valley, where it occurs under unconfined, or perched, conditions on top of the low-permeability lacustrine clays of the upper intermediate hydrogeologic zone. Where present, these clays generally act as a barrier between the shallow and deep zones. Figure 3-8 shows the locations of monitoring wells that are screened in the shallow hydrogeologic zone. The thickness of the shallow hydrogeologic zone ranges from 0 feet (that is, not present) at the margins of the China Lake playa to approximately 130 feet northeast of the intersection of Inyokern Road and Mahan Street. It should be noted that the shallow playa waters are technically in the fine sands and clays of the intermediate hydrogeologic zone where confining conditions exist rather than in alluvial sediments of the shallow hydrogeologic zone.

The depth to groundwater in the shallow hydrogeologic zone is generally shallowest in the eastern portion of the basin within the vicinity of the Lark and G-1 Seeps and the City of Ridgecrest sewage treatment ponds, ranging between 5 and 10 feet bgs. Toward the southern and western portion of the basin, the depth to groundwater deepens to about 90 feet bgs in the vicinity of the Desert Empire Fairgrounds to the south and to about 120 feet bgs at the SNORT Road Landfill (located northwest of the intersection of Inyokern Road and North Downs Road). The shallow hydrogeologic zone does not occur west of the Little Lake fault zone where it crosses North China Lake Boulevard (between West Las Flores Avenue and Ridgecrest Boulevard), as evidenced by lithologic logs and monitoring well completion reports for private gasoline stations (Gettler-Ryan Inc. 2001; Central Sierra Environmental 2001). First-encountered groundwater west of the Little Lake fault zone occurs within the intermediate hydrogeologic zone (upper portion of the regional aquifer) at depths greater than 140 feet bgs, most likely as a result of widespread pumping. The effects of these structural and sedimentary controls have been incorporated into the water table contour map presented on Figure 3-9.

Groundwater within the shallow hydrogeologic zone occurs under unconfined or water table conditions and generally flows toward the China Lake playa. An exception to this flow pattern is in the vicinity of the NAWs China Lake Public Works Compound where a groundwater mound is present and groundwater flows radially away from the mound, with the highest groundwater elevations measuring greater than 2,220 feet msl (Figure 3-9). Groundwater within the shallow hydrogeologic zone is generally not used as a viable water supply. What isolated contaminants have been found on the base are restricted to Navy property and have only affected groundwater within the shallow hydrogeologic zone. The following
discussion focuses on the current understanding of the occurrence and hydraulic properties of the shallow hydrogeologic zone.

Previous studies by the U.S. Geological Survey in the early 1980s indicated that groundwater elevations in and around the NAWS China Lake Public Works Compound and housing area were higher (mounded) relative to the surrounding shallow groundwater (Lipinski and Knochenmus 1981; St. Amand 1986; Banks 1982). A study conducted for the Navy by Leedshill-Herkenhoff (1983), which included the installation of 15 shallow wells, evaluated methods of lowering shallow groundwater in the vicinity of the City of Ridgecrest sewage treatment ponds, south of the China Lake playa. This measure was considered necessary at the time because 30 years of rising groundwater was causing drainage problems and structural damage to buildings. In the Leedshill-Herkenhoff report, the evolution of a groundwater mound was depicted from 1952 to 1982. By 1982, the mound had migrated southward roughly to the Public Works Compound, the current location. This movement reflects a shift in recharge sources away from the sewage treatment ponds to the Navy residential area. The Leedshill-Herkenhoff study implicated the following sources: infiltration from the sewage ponds, leakage from water distribution and wastewater pipelines, and lawn watering. St. Amand (1986) also suggested that the groundwater mound was due to lawn watering and leaky pipes. The infiltration sources likely have been reduced considerably since the 1982 Leedshill-Herkenhoff study since all civilian housing has been removed and the water distribution system has presumably been shut off. More detailed resolution of the groundwater mound was accomplished during the Navy’s recent fence line study (TtEMI and WGI 2001; TtEMI in press). The fence line water level measurements indicated that shallow groundwater elevations are as much as 50 feet higher in the vicinity of the Public Works Compound compared to those beneath the Satellite Lake playa to the southeast or the Area R alluvial-lacustrine flats to the north (TtEMI in press; TtEMI and WGI 2001; Figure 3-9). Although the mound still exists and appears to have stabilized, there is evidence that water levels have dropped over the last 20 years.

Several distinct lines of evidence were used to develop a hypothesis to explain the Public Works Compound groundwater mound (Figure 3-10). Information sources include active faults mapped by Roquemore and Zellmer (1987), recent groundwater studies along the fence line between Ridgecrest and the China Lake Complex (TtEMI and WGI 2001), investigations in the area of the NAWS Michelson Laboratory (TtEMI 1997), seismic reflection line NAWS-IWV-92-03 (Monastero and others 2002), seismic reflection line NAWS-IWV-00-10 (Figure 3-7), and field reconnaissance of the mound area in February 2002 by TtEMI.

Based on the new evidence, the structural geology underlying the groundwater mound can be interpreted as a broad rise or horst, which is flanked by wrench fault structural patterns. Compressive features,
including (1) a compressive splay of the Richmond School upthrust, (2) an associated terrace complex along the adjacent Little Lake fault zone trace, and (3) the rhomb-shaped shallow pull-apart graben in which the Mirror Lake playa developed, reflect recent surface expression of the basinwide neotectonic activity. The kinematics of these and other structural features in eastern California continue today, as evidenced by ongoing seismic activity (Peltzer and others 2001) and ground station movement velocities of 2 to 11 millimeters per year (McClusky and others 2001).

Groundwater elevations decrease radially away from the groundwater mound. The direction of shallow groundwater movement is to the north along the northern boundary of the Public Works Compound, to the south near Dewey Road, to the east along the eastern boundary of the Public Works Compound, and to the west extending off base along Inyokern Road due west of the Public Works Compound (Figure 3-9). Figure 3-11 shows a groundwater level profile along transect A-A’ that extends from the west along Inyokern Road to the east adjacent to Mirror Lake. Both the ground surface elevation and groundwater surface elevation (water table) are shown on the profile. The depth to groundwater (approximately 120 feet bgs), and corresponding groundwater elevation, is deepest at the western end of the profile (Figure 3-9). The groundwater mound is evident in the center of the profile as indicated by the groundwater levels measured in monitoring wells MKFL-MW01 (depth to water approximately 45 feet bgs) and MK69-MW01 (depth to water approximately 40 feet bgs). Groundwater elevations decrease at the eastern end of the profile. Horizontal groundwater gradients from the center of the mound were calculated to be 0.003 foot/foot to the northwest throughout 2001 (as calculated from wells MKFL-MW01 and MKFL-MW03), 0.004 foot/foot to the north (as calculated from wells MK69-MW01 and JMM07-MW11), and 0.010 foot/foot to the southeast (as calculated from wells MK69-MW01 and TTBK-MW02) (TtEMI in press).

A variety of aquifer tests have been conducted within the shallow hydrogeologic zone to estimate the hydraulic properties of this unit. These tests include both slug tests and aquifer pump tests (step drawdown and specific capacity tests) conducted at NAWS China Lake. Results of these tests show estimated hydraulic conductivities ranging between 0.22 and 65.21 feet per day and estimated transmissivities ranging between 823 and 5,400 gallons per day per foot (Table 3-2). The wide range of hydraulic conductivity and transmissivity estimates for the shallow hydrogeologic zone is consistent with the heterogeneous nature of the alluvial fan and alluvial deltaic facies that compose this unit. The lowest values are associated with shallow hydrogeologic zone wells screened within the lenticular beds of unconsolidated clays and silts of these facies (for example, wells JMM01-MW01 and JMM01-MW06), and the highest values are associated with the wells screened within the sands and gravels of the facies (for example, wells TTIWV-MW12 and TTIWV-MW14). Information obtained from well development pumping, step drawdown tests, and specific
capacity tests in the vicinity of the Public Works Compound has indicated that sustained yields of the shallow hydrogeologic zone wells range from less than 1 to 7 gallons per minute (TtEMI and WGI 2001).

Groundwater pumping from water supply wells that are screened in the intermediate and deep hydrogeologic zones of the regional aquifer appears to influence movement of groundwater in the shallow hydrogeologic zone in the south and southwestern portions of the basin. This interpretation is supported by the continued downward vertical gradients (indicated by a negative sign) calculated for well pairs as shown on the bar chart for transect A-A’ on Figure 3-12 and measured by velocity sensors (TtEMI and MK 2000b; TtEMI and WGI 2001; TtEMI in press). West of the Little Lake fault zone and northwest of Inyokern and North Downs Roads, the vertical gradient was calculated as -0.53 foot/foot at well pair MK12-MW16/MK12-MW17 (Figure 3-12). Within the Little Lake fault zone, the downward vertical hydraulic gradient between the shallow hydrogeologic zone and intermediate hydrogeologic zone of the regional aquifer is about -0.11 foot/foot (well pair MK12-MW12/MK12-MW11). These calculated gradients remained constant during 2000 and 2001 (TtEMI and WGI 2001; TtEMI in press).

A downward vertical gradient is also observed along the fence line east of the Little Lake fault zone, in the Public Works Compound and east to Mirror Lake (Figure 3-12). The vertical hydraulic gradient ranges between -0.40 foot/foot (well pair MK69-MW01/MK69-MW02) and -0.42 foot/foot (well pair MKFL-MW03/MKFL-MW04). The downward vertical gradient at Pilot Plant Road and South Richmond Road is about -0.05 foot/foot (well pair RLS22-MW01/MK22-MW10) (Figure 3-12). The greatest downward vertical gradients were noted in the vicinity of the southern portion of the base including well sites at or near the Public Works Compound (Figure 3-12). The effects of pumping from wells screened in the intermediate and deep hydrogeologic zones of the regional aquifer decrease with increasing distance away from the pumping wells in areas to the north and east, as evidenced by the water table contour map (Figure 3-9) and by the calculated vertical gradients (Figure 3-12). In areas where the silts and clays of the intermediate hydrogeologic zone are sufficiently thick, there is an upward vertical hydraulic gradient.

As shown on the bar chart for transect B-B’ on Figure 3-12, vertical gradients are upward in the well pairs screened in the shallow and intermediate hydrogeologic zones that are located within the vicinity of Armitage Field and near the City of Ridgecrest sewage treatment ponds and the NAWS China Lake golf course. For example, in the north central portion of the basin, near Armitage Field, the upward vertical gradient is 0.008 to 0.011 foot/foot (well pair ITC02-MW21/MW02-03). As a result, in this area groundwater is under upward pressure, reducing the possibility for downward movement of any potential
contaminants from the shallow hydrogeologic zone (TtEMI in press). Moreover, remedial investigations conducted along the southern NAWS China Lake property boundary and at the Public Works Compound, SNORT Road landfill, and Pilot Plant Road Landfill have demonstrated that there has not been any contaminated groundwater moving off base to the City of Ridgecrest (TtEMI and WGI 2001; TtEMI and MK 2000a).

3.2.2 Regional Aquifer

The regional aquifer is primarily composed of fan deposits of sands and gravels with some interbedded lacustrine clays. Groundwater within the regional aquifer may occur under confined, semiconfined, or unconfined conditions. Where the lacustrine clays are present, groundwater is semiconfined to confined. Groundwater conditions become unconfined where these clays pinch out. In general, the regional aquifer is unconfined in the vicinity of Inyokern and in the western- and southernmost portions of Ridgecrest, including the Southwest and Intermediate Well Field areas. In the eastern portion of the valley, the regional aquifer is confined or semiconfined by lenses of the lacustrine and playa deposits. Locations of key monitoring wells and production wells that are screened in the regional aquifer are shown on Figure 3-13. This figure also shows the transect lines for groundwater level profiles W-W' through Z-Z’. These four groundwater profiles, shown respectively on Figures 3-14 through 3-17, provide a comparison of ground surface elevations with groundwater level elevations measured in 2000 and 2001 for four transects across the Indian Wells Valley. On the first profile, W-W’ (Figure 3-14), which trends northwest to southeast across the Indian Wells Valley (Figure 3-13), groundwater level elevations to the northwest appear as a subdued replica of the ground surface elevations, indicating that unconfined (water table) conditions exist. In the vicinity of Highway 178 (Inyokern Road) and continuing to Bowman Road, the groundwater level elevations show a general depression that correlates to pumping in the vicinity of the Intermediate Well Field. On the second profile, X-X' (Figure 3-15), groundwater level elevations remain relatively flat, decreasing slightly in the vicinity of Brown Road and the NAWS boundary, and then approach the ground surface at the northeastern end of the profile transect past Range Road where confined conditions exist (Figure 3-13). On the third profile, Y-Y’ (Figure 3-16), the groundwater level elevations to the southwest near Little Dixie Wash also appear as a subdued replica of the ground surface, indicative of unconfined groundwater conditions. Proceeding along profile Y-Y’ to the northeast, the groundwater levels continue to decrease in the vicinity of the Intermediate Well Field and NAWS boundary (central portion of the profile), and increase near Armitage Field where confined groundwater conditions exist. On the fourth profile, Z-Z’ (Figure 3-17), there is a decrease in groundwater elevations in the vicinity of Jacks Ranch Road that extends about 2 miles to the northeast of Jacks Ranch Road, corresponding with the area of the Intermediate Well Field. A plan view of regional groundwater level
elevation contours for 2001 is provided on Figure 3-18. These groundwater elevation contours are based on groundwater level measurements taken by Kern County Water Agency personnel during the spring of 2001. Additional groundwater elevation contour maps for 1995 through 2000 are provided in Appendix B. Groundwater levels measured in wells screened in the regional aquifer are shallowest in the vicinity of the City of Ridgecrest sewage treatment ponds near the China Lake golf course, where depths to water ranged from 22 to 34 feet bgs in two wells with screened intervals beginning from 353 to 395 feet bgs. Groundwater levels are deepest south and west of the Intermediate Well Field (south of Inyokern Road and east of Jacks Ranch Road), with depths to water ranging from 220 to over 350 feet bgs (Figure 3-19). Additional maps that show depths to groundwater measured from 1995 through 2000 are provided in Appendix C.

Transtensional faulting has previously been suspected of influencing groundwater flow in the Indian Wells Valley. Many of the known and suspected northwest-trending Plio-Pleistocene fault traces were considered “barriers” to groundwater flow, including the Little Lake fault zone and Airport Lake fault zone. The Little Lake fault zone was considered the China Lake barrier. Steinpress and others (1994) suggested that the China Lake barrier was not the result of faulting but is in fact a west-to-east facies change from sand at the basin margin to silt and clay nearer to the lacustrine depocenter of the Indian Wells Valley basin. They also suggested that faulting per se does not appear to have a significant effect on regional groundwater flow in the upper Pleistocene and Holocene sediments of the eastern Indian Wells Valley. This observation is in agreement with Berenbrock and Martin (1991), who did not consider the faults in the Indian Wells Valley to be barriers to groundwater movement. More recent and detailed shallow groundwater studies along the fence line between NAWS China Lake and Ridgecrest that crosses the Little Lake fault suggest that subtle differences in groundwater elevations exist across the fault. Sediments within the shallow fault zones where sections are downdropped are often more coarse-grained and disturbed and lack stratification. Clay horizons are often fractured with slickensides. Detectable differences in hydraulic gradients and groundwater geochemistry in the fault zone are apparent but do not constitute a barrier in the hydrologic zones above 800 to 1,000 feet bgs (TtEMI 2003). Below these depths, groundwater flow has not been evaluated at a resolution necessary to address the groundwater barrier issue.

Most of the groundwater that is used as a regional source of water supply is pumped from the southwestern and western portions of the basin. The bottom of the deep hydrogeologic zone is defined by the contact with the underlying consolidated or crystalline bedrock. Based on geophysical studies conducted within the basin (Monastero and others 2001; Zbur 1963), as much as 6,500 feet of basin fill is
present in the western portion of the Indian Wells Valley, but the average depth of basin fill is more than approximately 4,000 feet based on the recent seismic refraction survey data.

The 2001 regional aquifer groundwater elevation contour map (Figure 3-18) shows the highest groundwater elevations occurring in Little Dixie Wash in the southwest corner of the basin (2,800 feet msl). The groundwater gradient is very steep in this region as evidenced by the water level elevation contours between wells USBR-1S and 27S/39E-08M02. These two wells are located approximately 13,000 feet apart, with water levels between these wells dropping approximately 485 feet, for an average gradient of 0.037 foot/foot. This is much steeper than elsewhere in the regional aquifer where pumping is not a factor. For comparison, groundwater gradients in the northern and eastern parts of the basin are approximately 0.0025 foot/foot. The steep gradient is also evident on groundwater level profile Y-Y’ (Figure 3-16). The steep gradient in the southwestern corner is probably related to faults associated with the Sierra Nevada frontal fault system (Zbur 1963; Monastero and others 2002).

The 2001 regional aquifer groundwater elevation contour map (Figure 3-18) also shows high water levels in the upper northwest portion of the basin and within Rose Valley (2,250 feet msl). Groundwater elevation contours indicate a southerly flow in this area, suggesting that groundwater is flowing in from Rose Valley. Bauer (2002) estimates that water is leaving Rose Valley at about 3,300 acre-feet per year (acre-ft/yr) and entering the Indian Wells Valley groundwater basin below the Little Lake gap. Transect W-W’ on the set of groundwater level profiles for the regional aquifer (Figure 3-14) also shows that the groundwater elevation is highest (2,250 feet msl) at the northwest corner of the groundwater basin and decreases by about 130 feet in the vicinity of the Intermediate Well Field. Hydrographs for selected wells are provided in Appendix D. The hydrograph for USBR-10 (24S/38E-22E) shows that groundwater levels have remained relatively constant following well development in 1996, except in one piezometer (USBR-10SM) screened from (perforation interval) 1,180 to 1,200 feet bgs that appears to be affected by agricultural pumping, as evidenced by a net decrease in water levels of over 6 feet in 6 years. The effects of pumping in this piezometer are distinguished from those in the shallow piezometer (screened between 640 and 660 feet), which has only shown a 2-foot decrease in water levels. Groundwater in the piezometer screened from 1,180 to 1,200 feet bgs is under confined conditions (as indicated by the occurrence of clay from 680 to 1,440 feet bgs), whereas groundwater in the shallow piezometer is under unconfined conditions (as indicated by cuttings of gravel or sand to a depth of 680 feet bgs). USBR-10 is located in the northwest portion of the valley within 1 mile east of the outfall of Nine Mile Canyon. As a result, the shallow piezometer may show signs of receiving limited recharge from two possible sources,
Rose Valley and Nine Mile Canyon. However, additional water level and age-dating (isotope) investigations would be necessary to confirm this.

The geometry of the Indian Wells Valley basin is expected to have an effect on the boundary conditions in the northwest portion of the basin near USBR-10. Groundwater movement in this area is to the south, controlled by a narrowing of the valley. Groundwater movement is restricted on the northwestern edge of the basin by bedrock from the Sierra Nevada and by lava flows east of Highway 395. The ground surface elevation decreases toward the south from about 2,560 feet msl at USBR-10 to 2,352 feet msl at USBR-6 (25S/38E-12L01) near the intersection of Highway 395 and Brown Road. Several agricultural wells in this area are completed at depths of 280 to 770 feet, with corresponding estimated subsurface elevations of approximately 1,580 to 2,070 feet msl, indicating that USBR-6S (with a perforation interval of 330 to 350 feet bgs [approximately 2,022 to 2,002 feet msl]) and likely USBR-10SM (with a perforation interval from 1,180 to 1,200 feet bgs [approximately 1,380 to 1,360 feet msl]) are being affected by agricultural pumping. Similarly, the hydrograph for well NR-1S (25S/38E-25J01), which is screened from 250 to 270 feet bgs, shows a groundwater level decrease of about a foot per year for the 7-year period of record (Appendix D).

A large pumping depression encompasses the Intermediate Well Field. This groundwater depression results from pumping of water supply wells, as well as agricultural and private supply wells. The effects of pumping in the Southwest and Intermediate Well Field areas are evident from the concentric contour lines decreasing in elevation toward the center of the well fields (Figure 3-18 and Appendix B). These flow patterns indicate that flow within the regional aquifer is strongly affected by pumping from water supply wells, particularly within the vicinity of Ridgecrest and the Intermediate Well Field. For example, inspection of the hydrograph for well MW-32 (26S/39E-27D) shows that within the vicinity of the Intermediate Well Field, groundwater levels have generally decreased at a rate of over a foot per year during the 6-year period of record (Appendix D). This trend is also reflected regionally in the groundwater elevation change map for a 5-year period from 1995 to 2000 (Figure 3-20).

A variety of aquifer tests have been conducted within the regional aquifer to estimate the hydraulic properties of this unit. These tests included both slug tests and aquifer pump tests ranging in duration from 48 to 64 hours. Results of these tests show estimated hydraulic conductivities ranging between 0.29 and 56.7 feet per day and estimated transmissivities ranging between 43 and 155,000 gallons per day per foot (Table 3-2). The wide range of hydraulic conductivity estimates for the regional aquifer is consistent with the heterogeneous nature of the alluvial fan, alluvial deltaic, and lacustrine facies that make up this regional aquifer unit. The lowest values are associated with regional aquifer wells screened within the clays and silts of these facies (for example, well TTIWV-MW16) and the highest values are associated with the wells
screened within the sands and gravels of the facies (for example, wells USBR-4 and TTIWV-MW07). The transmissivity estimates obtained from the aquifer pump tests (Kunkel and Chase 1969) are believed to be more representative of the regional aquifer than those obtained from the slug tests. This is due to the small volume of aquifer material that is tested in the slug tests and the potential for borehole properties to influence the results. The transmissivity estimates obtained from the aquifer performance tests range between 44,000 and 155,000 gallons per day per foot. Information obtained from specific capacity tests in the valley show that specific capacities of wells range between approximately 3.9 and 358 gallons per minute per foot of drawdown (Kunkel and Chase 1969; Lofgren & Associates 1989). The regional aquifer commonly yields more than 1,000 gallons per minute to wells, and some wells in the Inyokern area yield more than 2,000 gallons per minute (Berenbrock and Martin 1991; Lofgren 1989).

3.3 GROUNDWATER RECHARGE

Groundwater recharge in the Indian Wells Valley occurs from a combination of mostly natural and some man-made sources. The primary components of natural recharge to the groundwater system in the Indian Wells Valley identified by previous authors (Table 3-3) include infiltration of surface runoff from the Sierra Nevada, Coso, and Argus Ranges; subsurface inflow from the Sierra Nevada bedrock unit; geothermal upwelling; and subsurface inflow from Rose Valley. A small amount of recharge may also be occurring from infiltration of surface runoff from the El Paso Mountains in the southern portion of the basin. It is commonly agreed upon by researchers within the area that recharge via infiltration of direct precipitation within the valley is insignificant. The Navy conducted an experiment in 1997 that found that little or no artificial (man-made) or natural precipitation reached the groundwater in this study year (TiEMI 1999). Sources of artificial (man-made) recharge may also contribute to groundwater recharge on a localized and very limited basis. These sources include leakage from the Owens Valley aqueduct, leakage from the IWVWD distribution lines, leakage from wastewater treatment plants, and infiltration from irrigation water.

Various recharge studies have been conducted within the Indian Wells Valley and the associated estimates of recharge amounts obtained from them vary widely. One of the main disagreements between the individual researchers has to do with whether the Indian Wells Valley is treated as a closed basin or an open basin. In the closed basin model, the alluvial fill is enclosed by essentially impermeable bedrock and fault systems resulting in limited subsurface inflows or outflows within the basin. Natural outflow from a closed basin is through evapotranspiration. In the open basin model, there are natural subsurface and/or surface inflows and outflows (interbasin flows) within the basin via the underlying fractured bedrock unit and/or through the overlying alluvium.
Table 3-3 presents the range of reported recharge estimates for the Indian Wells Valley groundwater basin. As shown, estimates of total recharge range between approximately 9,850 acre-ft/yr or 3,210 mgy (Bloyd and Robson 1971) to approximately 49,000 acre-ft/yr or 15,967 mgy (Thompson 1929). Several researchers include components that suggest that the Indian Wells Valley is an open basin (for example, geothermal upwelling, interbasin flow from Rose Valley, and subsurface inflow from Sierra Nevada bedrock).

Estimates of geothermal upwelling range from 100 acre-ft/yr or 32.59 mgy (Bean 1989) to up to 10,000 acre-ft/yr or 3,259 mgy (Table 3-3). Estimates of interbasin flow from Rose Valley range between 40 acre-ft/yr or 13 mgy (St. Amand 1986) and 10,000 acre-ft/yr or 3,259 mgy (Thompson 1929). Bauer’s (2002) most recent estimate of interbasin flow from Rose Valley is 3,300 acre-ft/yr or 1,075 mgy. Estimates of subsurface inflow from fractured Sierra Nevada bedrock range between 2,500 acre-ft/yr or 815 mgy (Bean 1989) and 30,000 acre-ft/yr or 9,776 mgy (Thyne and others 1999). Ribble and Haslebacher (1999) estimated that 4,120 acre-ft/yr or 1,343 mgy enters the Indian Wells Valley from a single Sierra front canyon watershed, Grapevine Canyon. However, a review of historical precipitation data shows that the year the study was conducted, 1997, was a wet year. The community of Inyokern received 8.61 inches of rainfall during 1997/1998, whereas the annual average precipitation for Inyokern is 4.73 inches based on a 30-year average from 1971 through 2000. As a result, analyses of additional years should be made to better define the basin characteristics. Although there is clear evidence that these three recharge mechanisms are occurring within the Indian Wells Valley (for example, deep [>10,000 feet] bedrock wells within the Coso Range geothermal field producing water apparently derived from the Sierra Nevada based on groundwater isotopic data indicating interbasin flow through the fractured Sierra Nevada bedrock) (Fourier and Thompson 1982), there is marked disagreement regarding the actual amount of recharge associated with them. As mentioned in Section 3.5, it is suggested that additional studies be conducted to further determine the degree to which interbasin flow occurs within the Indian Wells Valley. These additional studies would in turn further constrain the estimates of total recharge.

Estimates of artificial (man-made) recharge are also provided in Table 3-3. As shown, there are only a limited number of estimates provided for artificial recharge, and the estimates vary considerably between the researchers. Leakage from the Owens Valley aqueduct was estimated to be approximately 900 acre-ft/yr (or 293 mgy) by Bean (1989) and 4,000 acre-ft/yr (or 1,303 mgy) by Austin. Recharge from agricultural irrigation was estimated to be approximately 100-acre-ft/yr (or 32 mgy) by Berenbrock and Martin (1991) and 2,000 acre-ft/yr (or 652 mgy) by St. Amand (1986). However, given the arid nature of the valley, high rate of evapotranspiration of approximately 80 inches per year (Berenbrock and Martin 1991), and depth to groundwater in the agricultural areas of the valley, the contribution of recharge from
irrigation is expected to be minimal. Recharge estimates associated with leakage from the Indian Wells Valley wastewater treatment plants range between approximately 400 (St. Amand 1986) and 1,000 acre-ft/yr (or 326 mgy) (Berenbrock and Martin 1991). Recharge associated with leakage from the IWVWD distribution lines was estimated to be 500 acre-ft/yr (or 163 mgy) by Bean (1989). Although recharge from artificial sources is believed to represent a relatively small portion of overall recharge in the Indian Wells Valley, the limited amount of data available for these sources combined with the wide range of estimates warrant additional investigations of their magnitude and location within the basin. The data gaps associated with the recharge estimates for the Indian Wells Valley are presented in Section 3.5.

### 3.4 GROUNDWATER DISCHARGE AND PRODUCTION

Groundwater is the sole source of potable water supply in the Indian Wells Valley and is used by NAWS China Lake, the IWVWD, the Inyokern Community Services District, Indian Wells Valley Airport District, IMC Global Inc., private well owners, and agricultural concerns. In the IWVWD Domestic Water System 1997 General Plan, four primary areas of water supply within the Indian Wells Valley basin are identified: the Ridgecrest Area, which generally lies within the City of Ridgecrest; the Intermediate Area, which lies between the City of Ridgecrest and the community of Inyokern; the Southwest Area, which lies to the southwest of Ridgecrest and south of Inyokern; and the Northwest Area, which lies to the northwest of Ridgecrest and north of Inyokern (Krieger & Stewart 1998). In 2001, the largest producers of groundwater in the Indian Wells Valley were the IWVWD (with production of approximately 8,393 acre-ft/yr or 2,735 mgy), private agricultural users (with production of 7,942 acre-ft/yr or 2,588 mgy), and NAWS China Lake (with production of 2,839 acre-ft/yr or 925 mgy). This information is presented graphically on Figure 3-21. Groundwater levels in the Ridgecrest Area and the Intermediate Area are declining at a rate of 1.0 to 1.5 feet per year, which affects production capacity within areas that are subject to the greatest amounts of groundwater withdrawal (Krieger & Stewart 1998). The greatest volume of water is extracted from the Southwest Well Field, which has been determined to contain a significant quantity of high quality water. Water in the Northwest Area, which has been used historically for agricultural purposes, has been reported to have TDS concentrations of over 500 milligrams per liter (mg/L). The following subsections discuss the water use of these major groundwater producers.

#### 3.4.1 NAWS China Lake

NAWS China Lake supplies water for the main population center at the China Lake Complex. For the period of record of 1945 to 2001, annual volumes of groundwater pumped have ranged from a low of 764
acre-ft/yr (or 249 mgy) in 1945 to a high of almost 7,979 acre-ft/yr (or 2,600 mgy) in 1970. Since 1970, the population and water requirements of NAWS China Lake have declined, and water use is now relatively constant at 2,840 acre-ft/yr (or 925 mgy). Figure 3-21 shows annual groundwater production from NAWS China Lake wells for the period between 1977 and 2001. NAWS China Lake production wells are generally screened between approximately 200 and 1,000 feet bgs in the regional aquifer.

The groundwater elevation contour map for May 2001 (Figure 3-18) shows that pumping depressions exist within the vicinity of the Intermediate Well Field, NAWS China Lake production wells, and agricultural supply wells. The effects of groundwater pumping are also evident on the regional aquifer groundwater elevation change map (Figure 3-20) and historical groundwater elevation contour maps presented in Appendix B.

3.4.2 Indian Wells Valley Water District

As the primary domestic water purveyor in the Indian Wells Valley, the IWVWD supplies water to the City of Ridgecrest for municipal and domestic users, with a 1997 service population of 36,000 people. The IWVWD’s domestic water system consists of 12 well pumping plants, 9 booster pumping plants, 10 water storage reservoirs, and over 1 million linear feet of transmission and distribution pipelines, and is divided into 5 separate pressure zones (Krieger & Stewart 1998). The locations of the IWVWD production wells located in the Ridgecrest and Intermediate Well Fields are shown on Figure 3-13. From January through December 2001, the IWVWD wells produced approximately 8,378 acre-ft (or 2,730 million gallons) of water, of which 1,547 acre-ft (or 504 million gallons) came from the Ridgecrest Well Field (wells IWVWD-7, IWVWD-11, IWVWD-13, and IWVWD-19) (Figure 3-22), 1,212 acre-ft (or 395 million gallons) came from the Intermediate Well Field (wells IWVWD-8, IWVWD-9, and IWVWD-10) (Figure 3-23), and 5,616 acre-ft (or 1,830 million gallons) came from the Southwest Well Field (wells IWVWD-17, IWVWD-18, IWVWD-30, IWVWD-31, and IWVWD-33) (Figure 3-24).

3.4.3 City of Ridgecrest

The City of Ridgecrest pumps groundwater at an annual rate of 20 acre-ft/yr (or 2 mgy) to irrigate seven parks, using wells that are screened in the regional aquifer. Leroy Jackson Regional Park is located south of Burroughs High School at French Road and Drummond Avenue. Kern Regional Park, located in the south Ridgecrest area approximately 3 miles southwest of the NAWS China Lake main gate, has a well that is screened from 150 to 250 feet bgs and 290 to 340 feet bgs, across the intermediate and deep hydrogeologic zones of the regional aquifer. Pearson Park is located over a mile southwest of the main
gate near the intersection of North Downs and Vicki Streets. Upjohn Park is located at Upjohn and Sunland. Hellmer’s Park is located at Warner Street just south of Ridgecrest Boulevard. Additional wells are located at the Little League/Kerr McGee Ball Fields and Veterans and Freedom Park at City Hall. Monthly production data for the park wells are unavailable, but water demand in the district is strongly dependent on season, with demand typically lowest from December to March and highest from June to September (Krieger & Stewart 1998).

3.4.4 Inyokern Community Services District

The Inyokern Community Services District serves approximately 420 households according to U.S. Census Bureau data for 2000. In 2001, the Inyokern Community Services District used 97 acre-ft/yr (or 32 mgy) of water. Water use has been steadily declining since the mid 1980s. This can be primarily attributed to reductions in the work force at NAWS China Lake.

3.4.5 Industrial Water Use

Unpublished data provided by the NAWS Environmental Project Office (2001) estimates that IMC Global uses groundwater at a rate of approximately 2,700 acre-ft/yr (or 880 mgy) for industrial and municipal water uses (EKCRCD 2003). Figure 3-21 shows total yearly production data for IMC Global wells. Private wells are used for light industrial applications in the vicinity of the Intermediate Well Field.

3.4.6 Agricultural Water Use

The use of water for irrigation in the Indian Wells Valley dates back to 1910, when a local farmer reportedly installed irrigation wells for growing alfalfa (USBR 1993). Numerous homestead wells throughout the Indian Wells Valley historically supported both domestic and agricultural water demands. Although many of these homestead wells still exist, they are inoperable and not currently in use. Current groundwater production for the irrigation of alfalfa occurs along the western boundary of the China Lake Complex and for various crops and orchards to the south of the China Lake Complex. Based on a field survey conducted in 1996, the EKCRCD estimated that the total production from private wells ranged from about 2,675 to 3,248 acre-ft/yr (or 872 to 1,058 mgy). Of this total, approximately 1,728 acre-ft/yr (or 563 mgy) was for residential production, and agricultural production was estimated to range from 947 to 1,520 acre-ft/yr (or 309 to 495 mgy). As shown on the historical summary of agricultural water supply usage for the Indian Wells Valley (Figure 3-21), 1985 represented the year of the greatest pumping for
irrigation at over 14,117 acre-ft/yr (or 4,600 mgy). Since that time, irrigation pumpage has declined to an approximate level of 7,672 acre-ft/yr (or 2,500 mgy).

3.4.7 Domestic Water Use

Many private wells are located in the neighborhoods on the western side of Ridgecrest in Sections 29, 30, and 31 of Township 26 South, Range 40 East. In 1993, the USBR estimated that approximately 3,000 private wells existed in the Indian Wells Valley and that approximately 550 of those were operational, producing approximately 2,099 acre-ft/yr (or 684 mgy). The USBR estimate is slightly higher than the estimate calculated in 1996 of 1,728 acre-ft/yr (or 563 mgy) by the EKCRCD.

3.5 DATA GAPS

Sections 3.1 through 3.4 have provided a framework for developing a hydrogeologic conceptual model for the Indian Wells Valley groundwater basin. This section identifies three primary aspects of the model for which there are gaps in the data and for which additional data should be collected to refine the current knowledge and understanding of the hydrogeology. These three aspects are as follows:

- The database needs to be expanded to include new monitoring locations and data.
- Water level fluctuations and hydraulic properties need to be quantified through direct or indirect field measurement techniques.
- The storage capacity and safe yield of the regional aquifer need to be quantified through numerical calculations using previously collected data and new field measurements.

Expanding the Database

Continuity is a must for a workable database. As a starting point, monitoring well locations need to be referenced to the same coordinate system, and preferably, with a consistent set of measuring devices and reference points. To accomplish this, a geodetic survey was performed in July and August 2001 at a total of 241 wellheads, target sites, and photo points that were positioned relative to previous precise geodetic control stations located at NAWS China Lake (National Imagery and Mapping Agency 2001). Geodetic latitudes, longitudes, ellipsoid heights, and elevations were determined to an accuracy of 0.03 meter relative to local World Geodetic System 84 control. All wells subsequently added to the monitoring well network should be surveyed using consistent methodology and the survey data added to the database, along with new water level and water quality data. Secondly, additional monitoring points, such as unsaturated/saturated monitoring systems in areas of suspected recharge, groundwater observation wells
or piezometers along the southwest margins of the basin, and gauging stations, would be useful. If additional monitoring points are added, exploratory boreholes should be continuously logged and sampled for geochemical and geotechnical parameters at key areas of stratigraphic change.

**Quantifying Water Level Fluctuations and Hydraulic Properties**

The primary areas regarding which there are gaps in the data are along the western margin of the basin, including the Southwest Well Field area; the west-central portion of the basin in the vicinity of Brown Road, the Northwest Well Field, and USBR-5 (25S/38E-34G) and USBR-6 (25S/38E-12L); and the extreme northwestern portion of the groundwater basin south of Rose Valley. Continuous groundwater level monitoring should be conducted to improve the current understanding of the interconnectivity between the hydrogeologic zones, determine the effects of groundwater production and discharge cycles, and determine the influence of natural phenomena such as earthquake activities. A network of pressure transducers placed in clustered observation wells or nested piezometers at strategic locations can be used to provide continuous measurements of both water level and temperature fluctuations. In addition, flow meters and gauging stations placed in the canyons and monitoring systems designed to measure both unsaturated and saturated flow conditions in drainage areas such as Little Dixie Wash in the southwest portion of the valley could be useful to quantify the amount of recharge entering the western margin of the groundwater basin. Aquifer testing could also be used to refine hydraulic property data and to quantify heterogeneities in various hydrogeologic zones across the basin.

**Quantifying Storage Capacity and Safe Yield**

The hydrogeologic conceptual model presented in this document is based on a review of existing information and provides ranges of values for recharge estimates and aquifer hydraulic properties. Likewise, there are unknowns associated with the interconnectivity and flow characteristics within the hydrostratigraphic units and groundwater basins. A hydrologic budget should be developed for the conceptual model that includes the characteristics and volume estimates for sources of recharge, discharge, and changes in groundwater basin storage. Water balance equations, coupled with numerical modeling, can be used to estimate the storage capacity and safe yield of the regional aquifer system.
4.0 WATER QUALITY

Groundwater quality data for the China Lake area have been collected for decades. The underlying goal has been the identification of areas where the water is of a quality suitable for drinking without treatment. Lee (1913) collected basinwide groundwater data in the early 1900s. Moyle (1963) collected water quality data in the early 1960s. Berenbrock (1987) compiled groundwater quality data for the period between 1977 and 1984. Whelan and Baskin (1989) used data collected from several sources to map groundwater quality in the Indian Wells Valley. Houghton (1994) provided a comprehensive review of existing data and classified the groundwater in the Indian Wells Valley into three basic groups. Thyne and others (1999) divided water into the Indian Wells Valley, Little Lake, and Southwest Wells Groups, plus a Sierran Group from springs and streams in the topographic watershed of the southwestern Indian Wells Valley. TtEMI (2002) slightly modified Houghton’s classification, grouping groundwater into four types. Sixteen additional monitoring wells in the Indian Wells Valley were installed and sampled as part of the Navy’s basewide study (TtEMI 2003), providing significant new data on water quality in the Indian Wells Valley. The following text focuses on the new data, with some comparisons to previous results.

4.1 BACKGROUND WATER QUALITY

At least three major factors affect the background groundwater quality in the Indian Wells Valley: geochemistry of the parent rocks and soils, the amount of time the water resides in a given formation, and mixing of waters. The background water quality of the perched shallow groundwater system and regional aquifer is discussed in the following subsections.

4.1.1 Shallow Hydrogeologic Zone

Water quality in the shallow hydrogeologic zone exhibits greater variability than that in the regional aquifer. Groundwater in the shallow hydrogeologic zone interacts with many different sediment types, ranging from alluvium derived from granitic terrains to fine-grained sediments. High evaporation rates in the vicinity of the China Lake playa tend to concentrate the cations and anions. The Piper diagram for the wells screened in the shallow hydrogeologic zone (Figure 4-1) shows that the majority of samples are of the sodium bicarbonate or sodium chloride types, with a few samples of the calcium sulfate or sodium sulfate types. A trend line is present on the cation portion of the Piper diagram ranging from a calcium-magnesium type water toward a sodium-dominated water. This suggests that cation exchange processes (natural water softening) are occurring in the shallow hydrogeologic zone, with sodium ions from the aquifer matrix replacing calcium and magnesium in the groundwater. Clay minerals are known to act as cation exchange media under certain conditions. Several of the monitoring wells screened in the shallow
hydrogeologic zone that contain soft water also show (1) elevated fluoride concentrations, (2) very high alkalinity values, and (3) low or nondetect sulfate concentrations.

Figure 4-2 presents Stiff diagrams that show spatial trends in groundwater quality. Shallow groundwater in the southwest portion of the basin has roughly equal proportions of the major anions (chloride, bicarbonate, and sulfate) and cations (sodium, potassium, calcium, and magnesium). An example is found in well RLS12-MW04. Water quality tends to decline toward the east and north as evidenced by higher concentrations of dissolved constituents. This is indicated graphically, with the size of the Stiff diagrams increasing for the shallow hydrogeologic zone wells towards the northeast from the Ridgecrest area.

There appears to be a natural increase of sodium towards the north, with water samples from the northern portion of the Indian Wells Valley containing naturally elevated concentrations of sodium and calcium, as shown on the Stiff diagrams for wells TTIWV-MW13 and TTIWV-MW14. Samples from several wells in the vicinity of the China Lake playa have TDS concentrations that exceed the State Water Resources Control Board Sources of Drinking Water Policy level of 3,000 mg/L, indicating that shallow groundwater in this region is likely unsuitable for municipal or domestic supply.

Groundwater in the shallow hydrogeologic zone exhibits naturally occurring arsenic at concentrations in excess of the new federal maximum contaminant level of 10 micrograms per liter (µg/L) (TtEMI 2003). Concentrations in samples from wells screened in the shallow hydrogeologic zone ranged between 5 µg/L (TTBK-MW02) and 500 µg/L (TTBK-MW13). The locations of these monitoring wells are shown on Figure 4-2. Wells with higher arsenic concentrations are generally located near the China Lake playa.

Some wells located near Navy Installation Restoration Program sites appear to show evidence of anthropogenic impacts on the shallow hydrogeologic zone. Stiff diagrams for three wells near Michelson Laboratory (JMM07-MW13, RLS07-MW04, and RLS34-MW06) show very high concentrations of sulfate, chloride, and potassium. Samples from wells to the south of these have TDS concentrations on the order of 200 mg/L, whereas samples from these three wells have TDS concentrations ranging between 6,900 and 7,900 mg/L (TtEMI 2003). The elevated TDS levels at these locations are attributed to site-related activities.

The water in shallow hydrogeologic zone well TTIWV-MW09, located on the east side of the ancestral China Lake, exhibits high concentrations of chloride, carbonate and bicarbonate, sodium, and potassium. This is very similar to the water quality in an adjacent regional aquifer well (TTIWV-MW10) completed
in fractured bedrock and in a similarly completed well in the Salt Wells Valley (TTSWV-MW10). The high confining pressures experienced while drilling in the China Lake playa area indicate the potential for upward movement of deep groundwater on the eastern side of the Indian Wells Valley and the potential for underflow through fractures into the Salt Wells Valley.

4.1.2 Regional Aquifer

Figure 4-3 presents the Piper diagram for the wells that are screened in the regional aquifer. Approximately half of the water samples may be classified as sodium bicarbonate in nature, one third as sodium chloride, and the remainder as a mixture of these two end points. The character of the groundwater in the regional aquifer along the western and southwestern portions of the Indian Wells Valley is typically sodium bicarbonate.

Stiff diagrams (Figure 4-2) for regional aquifer wells in the southwest portion of the Indian Wells Valley indicate that the anion and cation concentrations are low and that the water is of good quality. TDS concentrations are generally less than 500 mg/L in wells located in the vicinity of the IWVWD supply wells; however, concentrations increase to the north and east. The TDS concentration of 6,634 mg/L in the sample from USBR-3D is an exception to this trend. The screen interval in this well is from 1,850 to 1,870 feet bgs, below a clay interval approximately 350 feet thick. Figure 4-2 depicts the approximate location where TDS concentrations in the regional aquifer transition from less than 500 mg/L to greater than 500 mg/L. This transition is also evident on the TDS concentration isopleth map, contoured by the Kern County Water Agency in July 1995 and presented in Appendix E. The 500-mg/L concentration is a secondary maximum contaminant level for drinking water.

Arsenic concentrations were measured in wells screened in the regional aquifer as part of the Navy’s basewide study (TtEMI 2003). Arsenic concentrations ranged from 5 µg/L (TTIWV-MW08) to 61.7 µg/L (TTIWV-MW06), which exceeds the new federal maximum contaminant level of 10 µg/L.

Pumping of water supply wells in the Intermediate Well Field has created a cone of depression that extends north of the 500-mg/L TDS transition zone (Figure 4-2). The potential for deterioration of groundwater quality with continued pumping in this area can best be evaluated using groundwater-modeling techniques. The development of groundwater resources in areas southwest of the Intermediate Well Field such as Little Dixie Wash should lessen the likelihood of drawing in poorer quality water from the north and east and at depth in areas isolated by lacustrine sediments.
Water quality in TTIWV-MW16 is anomalous when compared to that in other regional aquifer wells (Figure 4-2). For example, TDS in samples from well TTIWV-MW16 has been measured at 35,000 mg/L. The sodium concentration is very high (10,360 mg/L), while the calcium and magnesium concentrations are very low (0.519 and 0.119 mg/L, respectively). The pH measured in this well is above 9.0, and sulfate has not been detected. As discussed later in this report, the age date of groundwater from this well was the oldest measured in the basin, greater than 49,000 ybp. During drilling of this well, it was noted that zeolite minerals were present. Zeolites act as water softeners, and it is likely that the zeolites in the aquifer are providing a natural cation exchange medium, leading to the evolution of soda water. TDS concentrations are also greater than 500 mg/L in four other wells completed in the regional aquifer: NR-1D (also known as 25S/38E-25J03, which is screened from 1,960 to 1,980 ft bgs), NR-2D (also known as 25S/38E-36G01D, screened from 1,910 to 1,930 ft bgs), USBR-3D (also known as 27S/39E-11D03, screened from 1,850 to 1,870 ft bgs), and TTIWV-MW06 (screened from 938 to 958 ft bgs). Although previous investigators (USBR 1993; Berenbrock and Martin 1991) have suggested that groundwater of good quality exists at depth, samples from these wells provide a note of caution that higher TDS water is found at depth in areas isolated by lacustrine sediments.

4.2 AGE DATING ANALYSIS

Groundwater samples were collected for the Navy basewide study (TtEMI 2003) to determine their isotopic composition on two occasions. The first sampling event was performed in February/March of 2000 and the second was conducted in February 2002. The respective sample results are presented in Tables 4-1 and 4-2. The earlier effort included collection of samples from 45 existing groundwater monitoring wells, 4 surface water bodies, and 1 spring, in addition to 1 precipitation sample. The samples were analyzed for various combinations of 14 different isotopes and intrinsic tracers. The second event involved analysis of groundwater samples from 32 monitoring wells installed in the Indian Wells Valley and the Salt Wells Valley for a targeted suite of isotopes. Bassett and Einloth (2000) and Thyne and others (1999) also performed isotopic analysis of groundwater samples from the Indian Wells Valley. Houghton (1994; Houghton HydroGeo-Logic 1996) measured isotopic oxygen ratios and deuterium in both surface water and groundwater from the Indian Wells Valley.

4.2.1 Isotopes and Intrinsic Tracers

Isotopes are distributed differently throughout water systems as a function of the chemical and physical conditions that existed during and after waters entered the hydrosphere. Groundwater samples were analyzed for both stable and radioactive isotopes. The stable isotopes are reported as the ratio of the predominant isotopes. For the Navy basewide study conducted by TtEMI, the following stable isotope
pairs were measured: (1) $^{18}\text{O}/^{16}\text{O}$, or $\delta^{18}\text{O}$; (2) deuterium/protium, or $\delta\text{D}$; (3) $^{13}\text{C}/^{12}\text{C}$, or $\delta^{13}\text{C}$; (4) $^{11}\text{B}/^{10}\text{B}$, or $\delta^{11}\text{B}$; (5) $^{87}\text{Sr}/^{86}\text{Sr}$; (6) $^{37}\text{Cl}/^{35}\text{Cl}$, or $\delta^{37}\text{Cl}$; and (7) $^{34}\text{S}/^{32}\text{S}$, or $\delta^{34}\text{S}$. $\delta^{18}\text{O}$ and $\delta\text{D}$ can be used to identify the origins and mixing of water that has been recharged under differing paleoclimatic conditions, at different elevations, or possibly impacted by ion exchange or evaporation. Isotopic enrichment or depletion is reported as a ratio expressed using the $\delta$ notation and is calculated as a difference relative to a standard. A sample enriched in the heavier isotope has a positive $\delta$ value, indicating that the isotopic ratio is greater than that of the standard reference material. Standard mean ocean water is the reference material used for $\delta^{18}\text{O}$ and $\delta\text{D}$ isotope analyses. The stable isotopes were useful in comparing different water-bearing zones and their evolution. The radioactive isotope $^{14}\text{C}$ was used to age date groundwater at the site. Chlorofluorocarbons (CFC) and the radioactive isotopes tritium ($^3\text{H}$), chlorine-36 ($^{36}\text{Cl}$), and radon ($^{222}\text{Rn}$) were analyzed for use as tracers. Tracers, in this context, are chemicals that can be used to evaluate the movement of groundwater from a known or hypothetical source area to the present location.

Tritium, a radioactive isotope of hydrogen with a short half life and therefore useful for determining modern recharge and mixing scenarios, was measured in three recent studies conducted by Thyne and others (1999), Bassett and Einloth (2000), and TtEMI (2003). Significant anthropogenic tritium was produced during atmospheric nuclear testing from 1952 to 1963, and precipitation from this era shows increased levels. Thyne and others (1999) used tritium data to support post-1952 recharge from influx of waters into the Indian Wells Valley. Their high tritium values for water from the IWVWD wells are suspect, however, since water-bearing zones of the same age were presumably sampled by the two studies sponsored by the Navy with very different results. Bassett and Einloth (2000) looked at several isotopes at the Navy’s request, including tritium, in an effort to determine what isotopes would be useful in future studies in the basin. They concluded that little recent water was mixing in the water-bearing zones sampled and suggested resampling the IWVWD wells. For the Navy’s basewide study (TtEMI 2003), the tritium levels were generally found to be low in the regional aquifer and somewhat higher in the more shallow wells. The study concluded that little mixing was taking place between the deeper waters and the clay-separated shallow hydrogeologic zones where the slightly elevated tritium levels provided evidence suggesting more modern recharge. Since most of the waters in the regional aquifer were found to be significantly older than 1952 based on $^{14}\text{C}$ results, tritium’s most direct and useful application is to valley margin recharge studies.
During the basewide study, it was concluded from the 2000 sampling that the most informative isotopic results were those of $\delta^{18}$O, $\delta$D, and $^{14}$C (TtEMI 2003). Therefore, a second round of samples collected in February 2002 were analyzed only for those isotopes.

4.2.2 Results of Isotopic Analysis

Approximately one hundred stable isotope measurements were used during the basewide study to describe geochemical processes or local variability in the depositional environments. The most useful isotopes with regard to comparing the different water-bearing zones were $\delta^{18}$O, $\delta$D, and $^{87}$Sr/$^{86}$Sr.

4.2.2.1 Shallow Hydrogeologic Zone

In general, the shallow hydrogeologic zone is more susceptible to impact from anthropogenic sources as well as chemical and physical fractionation. This is evidenced by (1) enrichment of $\delta^{11}$B, likely associated with evaporation and the presence of B-bearing minerals, and (2) depletion of $\delta^{34}$S, possibly associated with conditions of high oxidation and reduction potential.

$\delta$D and $\delta^{18}$O

The isotopic signatures for the shallow hydrogeologic zone are enriched for both $\delta^{18}$O and $\delta$D. The shallow hydrogeologic zone waters reflect evaporative enrichment in the heavier isotopes and some degree of modern recharge. Recent groundwater recharge tends to be enriched for both $\delta^{18}$O and $\delta$D, because climatic conditions during recent times have generally been warmer and drier than those during the Pleistocene. These signatures, therefore, differ from those for groundwater in the regional aquifer as discussed later in this section.

$^{87}$Sr/$^{86}$Sr

The majority of the observed $^{87}$Sr/$^{86}$Sr values for groundwater in Indian Wells Valley are similar to the $^{87}$Sr/$^{86}$Sr values for the Mesozoic plutons of the Sierra Nevada. Groundwater can be concluded to be in equilibrium with the current host rock or sediment.

Intrinsic Tracers

Of the intrinsic tracers analyzed, tritium and CFCs were the most useful. Modern recharge into the shallow hydrogeologic zone was confirmed by the presence of CFCs in shallow hydrogeologic zone samples from areas near Inyokern Road, Armitage Field, and Michelson Laboratory. Slightly elevated tritium results suggest modern recharge from surface runoff in the shallow hydrogeologic zone. The
principal sources of recharge in these areas are likely managed surface water runoff, leaking water pipes, washdown facility operations, or unlined surface water management ponds.

$^{14}$C Groundwater Ages

Estimated ages for groundwater in the shallow hydrogeologic zone using $^{14}$C concentrations ranged from modern (post 1950) to 27,540 ybp, with most ages less than 10,000 ybp (Figure 4-4). This implies that Holocene age recharge is the dominant source of water in this zone and is from natural recharge mechanisms along the mountain fronts, infrequent significant storm events, or recent water distribution practices.

4.2.2.2 Regional Aquifer

$\delta$D and $\delta^{18}$O

In general, the regional aquifer waters are depleted (isotopically lighter) in $\delta^{18}$O and $\delta$D as compared to groundwater in the shallow hydrogeologic zone. For example, the shallow groundwater sample most depleted in $\delta^{18}$O was from well TTIWV-MW09 with a value of -12.9 ‰ (Figure 4-4). This compares to the most depleted regional aquifer sample from TTIWV-MW07, which had a value of -14.3 ‰ for $\delta^{18}$O (Figure 4-5). For $\delta$D, the corresponding values for the shallow hydrogeologic zone and the regional aquifer were -103 ‰ (TTIWV-MW14) and -106 ‰ (TTIWV-MW07), respectively. Houghton HydroGeo-Logic (1996) reported a similar range of values for samples from eight NAWS China Lake monitoring wells. Houghton’s previous study (1994) of surface waters recharging to the Indian Wells Valley yielded values of -10.1 to 14.3 ‰ for $\delta^{18}$O and -82 to 107 ‰ for $\delta$D. (This is a typical range of values for meteoric-derived surface waters in this region.) The isotopically light groundwater from the regional aquifer represents Pleistocene recharge that infiltrated under cooler climatic conditions and/or at higher elevations.

A notable exception to this trend is the sample from well TTIWV-MW16, which had $\delta^{18}$O and $\delta$D values of -9.8 and -89 ‰, respectively. This well also had an extremely high TDS concentration of 33,500 mg/L. The heavy isotopic signature and high TDS are likely attributable to evaporative concentration of heavy isotopes and dissolved solutes in the source water prior to infiltration and groundwater recharge, most likely in a playa environment. Another contribution in this deeper stratigraphic zone is the dissolution and alteration of the vitric tuffs and other volcanic rock types, resulting in the creation of zeolite mineral assemblages with ion exchange processes that further increase the TDS concentrations.
$^{87}\text{Sr}/^{86}\text{Sr}$

The $^{87}\text{Sr}/^{86}\text{Sr}$ values for groundwater in the regional aquifer are similar to those for groundwater in the shallow hydrogeologic zone. The $^{87}\text{Sr}/^{86}\text{Sr}$ signature is in equilibrium with the $^{87}\text{Sr}/^{86}\text{Sr}$ signature of the Mesozoic plutons in the immediate area. Since the basin fill is predominately Mesozoic alluvium, it is not possible to state that equilibrium conditions reflect a groundwater source as opposed to equilibrium that is a result of the residence time of groundwater in the basin.

$^{14}\text{C}$ Groundwater Ages

The reported $^{14}\text{C}$ ages for groundwater in the regional aquifer range between 4,305 and greater than 49,000 ybp ($^{14}\text{C}$ cannot reliably be used to date materials older than about 49,000 ybp). The age dates for water from wells located in areas where the regional aquifer is a confined system are generally older than in areas where there is no confining layer. Some of the oldest ages were measured in samples from wells completed in the discontinuous sands and gravels of the regional aquifer. These old waters are thought to reflect connate conditions, with the waters effectively trapped in the sediments at the time of deposition. Some of the deeper waters appear to be “younger” than expected at these stratigraphic depths, which suggests some amount of mixing from younger Pleistocene waters. For example, as shown on Figure 4-5, a groundwater sample collected from well 27S/38E-13A01 on the topographic rise above Little Dixie Wash has an age of 4,305 ybp, suggesting Holocene recharge. Water from well TTIWV-MW01D yields a date of 19,908 ybp. Moving eastward along Inyokern Road, wells TTIWV-MW02D (23,006 ybp), TTIWV-MW04 (30,937 ybp), TTIWV-MW07 (32,836 ybp) and TTIWV-MW08 (38,958 ybp) show progressively increasing ages in the regional aquifer, which may be due to younger waters moving eastward from the western recharge areas. In general, the $^{14}\text{C}$ results show that groundwater age increases with depth and distance from the Sierra Nevada, supporting the concept that much of the regional aquifer groundwater represents Pleistocene recharge (Tables 4-1 and 4-2).

4.3 DATA GAPS

To date, the water quality and isotopic analyses have been crucial to defining the conditions in the Indian Wells Valley groundwater basin and the groundwater geochemical character and ages used in the conceptual model. However, a few more targeted data points would be helpful to fill in data gaps related to groundwater quality, groundwater mixing within and between different sediment types and hydrostratigraphic layers, and groundwater flow properties within the Indian Wells Valley groundwater basin, as follows:

- The set of wells sampled and analyzed for the targeted suite of isotopes needs to be expanded to include the western, southwestern, and northwestern wells. Seven USBR wells (USBR-1, -2, -3, -4, -5, -6, and -10), five IWVWD wells (IWVWD-12, -16, -32, NR-1, and NR-2), and the two Navy Seabee wells (FRCR01 and SWCB01) located in the El Paso Basin should be included.
Also, samples should be collected from a few key potential recharge areas and watershed locations and analyzed for the same isotopic suite.

- A groundwater monitoring plan needs to be developed to monitor inorganics and TDS to assist in determining water quality changes over time in key monitoring wells and production wells.

- Recharge along the Indian Wells Valley margins needs to be quantified successfully. Besides using traditional recharge evaluations, new isotopic analysis methods such as analysis for silicon-32 (\(^{32}\text{Si}\)) should be considered to explore vadose zone recharge.

**Expand Isotopic Sampling**

The current sample set for isotopic analyses and age dating does not include samples from the western, southwestern, and northwestern areas of the Indian Wells Valley, as well as current production waters. This data gap was pointed out in the USBR (1993) effort and is still unfilled. Since the Navy performed most of the extensive isotopic analyses and age dating to support their environmental goals, the current data do not address the margins of the basin, potentially important sources of present and future groundwater. In particular, the USBR wells and selected production wells should be considered a priority for a targeted practical suite of isotopic analysis. Certain wells sampled in previous studies should be resampled.

**Monitor Water Quality and Chemistry**

Baseline water quality should be established in all newly completed production and monitoring wells. Periodic monitoring of the groundwater quality in key wells in the monitoring well network should be conducted to check for long-term changes that may be the precursor of degraded water quality and movement of water types.

**Conduct Recharge and Watershed Studies**

Studies of the watershed and recharge provide valuable information necessary to establish the long-term viability of the groundwater resource. Ribble and Haslebacher’s (1999) study of Grapevine Canyon illustrates an excellent approach to studying the water yields from one of 15 or so watersheds along the Sierra Nevada front. Similar efforts coupled with isotopic analyses and age dating would be extremely useful in reducing the uncertainties of the recharge estimates. Extrapolations from a measured small watershed, such as Short Canyon, and from a large watershed, such as Grapevine or Sand Canyon, would be required because of the impracticality of covering all basins. Additionally, a promising new method of estimating recharge using \(^{32}\text{Si}\) is being investigated at the University of Arizona and New Mexico Tech that may have application here as another method of water age-dating. The \(^{32}\text{Si}\) method attempts to measure the silicon in soil and develops exchange rates between the \(^{32}\text{Si}\) and water. The technique can be
applied to quantifying long-term recharge from streams, washes, and mountain ranges. The soil is collected from core samples, and a large water sample is required to perform the separation and equilibrium processes necessary. The scintillation counting may require several months for the required precision, so the technique as available now has considerable promise but is time consuming. $^{32}$Si analysis can be coupled with traditional methods of recharge research using unsaturated/saturated flow monitoring systems; hydraulic gradients and water balances; soil moisture; depth profiles; chloride mass balance; and deuterium, tritium, $^{18}$O, and radiocarbon values. If it becomes practical, $^{32}$Si will have the advantage of bridging the data gap between $^{14}$C and tritium age dating spanning the 50 to 1,100 ybp time frame.
5.0 GROUNDWATER USABILITY

5.1 INFLUENCE OF HISTORICAL AND RECENT PUMPING ON THE STUDY AREA

As stated in Section 3.4, the largest producers of groundwater in the Indian Wells Valley have historically been and are presently the IWVWD, private agricultural users, NAWS China Lake, and IMC Global. Other significant producers of groundwater include the City of Ridgecrest, Indian Wells Valley residential and agricultural producers, and the Inyokern Community Services District. Figure 3-21 shows total groundwater production in Indian Wells Valley by major source for the years 1977 through 2001. The following section discusses the influence of these regional groundwater withdrawals on groundwater levels in the Indian Wells Valley with an emphasis on the period between 1995 and 2001.

The influence of regional pumping can be seen on a long-term (greater than 20 years), short-term (seasonal), and daily basis. Most of the hydrographs in Appendix D clearly display the effects of long-term pumping in the Indian Wells Valley; groundwater levels have declined approximately a foot per year since the early 1960s. This declining trend in groundwater levels of about 1.0 to 1.5 feet per year has been previously reported in the Ridgecrest and Intermediate Well Field areas (Krieger & Stewart 1998).

Monthly water production requirements vary seasonally with the weather (Krieger & Stewart 1998). Temperatures in the Indian Wells Valley increase substantially in the summer months and cause significant increases in water demands. Historically, high demands have occurred from June through September, with maximum daily demands normally occurring in July and August but occasionally in June. Low demands have normally occurred from December through March, with minimum demands occurring in January and February. These seasonal trends are readily apparent in the production well data (TtEMI 2003).

Daily water demands are generally very low during the early morning hours and increase during the late morning and afternoon hours (Krieger & Stewart 1998). Maximum daily water demands are often correlated with the seasonal water demands. Cyclical perturbations have been noted in the continuous (hourly) measurements collected from both the pressure transducer and velocity sensor data loggers (TtEMI and WGI 2001; TtEMI in press). Although the cyclical perturbations are slight (hundredths of a foot), they have been noted on a consistent basis and are believed to be a result of daily water use patterns.
According to IWVWD (2002), between 1921 and 1988, groundwater levels in the basin declined about 80 feet in the area of the Intermediate Well Field. Figure 3-20 shows the regional aquifer groundwater elevation change over most of the Indian Wells Valley for the period 1995 to 2000. The map shows that groundwater levels throughout the Indian Wells Valley declined approximately 1 to 10 feet over the period, with the greatest declines being observed in the areas of the Intermediate Well Field and NAWS China Lake production wells. Significant groundwater elevation change also occurred to the north and west in the area of increased agricultural withdrawal.

There was an overall shift in groundwater production from 2000 to 2001, with over half of the groundwater supply coming from the Southwest Well Field. The contour map for 2001 for the regional aquifer (Figure 3-18) shows a slight shifting and increase in gradient to the west toward the Southwest Well Field from the previous years (Appendix B) (also noted in TtEMI and WGI 2001).

5.2 PROJECTION OF FUTURE GROUNDWATER USAGE

Figure 5-1 shows the past, current, and projected groundwater use for the Indian Wells Valley from 1990 through 2020. It also shows that the highest recent total annual water production was 23,994 acre-ft/yr (or 7,821 mgy) in 1997. From 1998 to 2002, the average total annual water demand declined from the 1997 high. This reduction in water use can be attributed to the downsizing of NAWS China Lake and the associated loss of infrastructure. Additional but smaller effects may be related to water conservation programs, pipeline upgrades, meter installation programs, computer hardware and software upgrades for monitoring water use and pipeline systems, and a tiered rate structure for consumption within the IWV service area (IWVWD 2002). Figures 3-21 and 5-1 indicate that total groundwater withdrawals have been declining at NAWS China Lake since the early 1980s.

If one considers the total groundwater demand in the IWVWD over the past 5 years (1998 through 2002), the average annual increase over this period may be estimated at 2 percent (similar to projection rates determined by the IWVWD [2002]). This estimated increase assumes the continuation of the water conservation programs that are presently in place. These water conservation programs include, but are not limited to, new plumbing efficiency standards, water audits, leak detection programs, and public information programs. Since this report addresses multiple groundwater users, a more accurate method of determining projected total groundwater production in the Indian Wells Valley involves analyzing recent (past 5 years) production trends for each individual producer and assessing this rate of increase along with other available data, such as demographic information available on-line and from the USBR (1993), IWVWD (2002), and the NAWS Environmental Impact Statement (NAWS Public Affairs Office 2002).
Individual rates of increase or decrease used in the projections shown on Figure 5-1 were determined from the past 5 years of available production data. In some cases, rates of increase or decrease were changed to reflect actual demographic trends or to account for other likely changes in water use.

Producers with the greatest projected increases in water use are the IWVWD and small residential producers that are projected to increase production at an average annual rate of 2 and 1 percent respectively, through the year 2020. Total agricultural use and groundwater use by IMC Global are projected to increase annually by about 0.01 percent. The Inyokern Community Services District and NAWS China Lake are each projected to experience decreases in annual groundwater production of 0.05 percent per year. The estimated combined effect on projected total annual groundwater production in the Indian Wells Valley is a net annual increase of 0.09 percent. This translates to an estimated increase in Indian Wells Valley total production from 21,401 acre-ft/yr (or 6,974 mgy) in 2002 to 22,867 acre-ft/yr (or 7,451 mgy) in 2020.

The following sections briefly discuss key supporting information used to determine projected rates of groundwater production for each Indian Wells Valley producer.

5.2.1 NAWS China Lake

Since 1970, the population and water requirements of NAWS China Lake have declined, and water use is now relatively constant at about 2,839 acre-ft/yr (or 925 mgy). A 0.05 percent annual decline in production is projected to 2020 as a result of increased conservation and water use accounting programs.

5.2.2 Indian Wells Valley Water District

As a result of conservation programs and programs to more closely account for water use in the district, water demands are expected to increase by an estimated 2 percent annually until 2020. The district anticipates adding new connections at a rate of about 1 percent per year, but because of new plumbing efficiency standards, landscaping guidelines, and other conservation programs, water demand has not matched the connection growth (IWVWD 2002).

5.2.3 City of Ridgecrest

Groundwater production is assumed to remain constant at 20 acre-ft/yr (or 6.5 mgy) or decrease slightly based on limited population growth and continued irrigation practices.
5.2.4 Inyokern Community Services District

Annual groundwater production in the Inyokern Community Services District has slowly declined over the period of record (1977 to present). There is little to suggest that the rate of decline will change significantly (approximately 0.05 percent annually).

5.2.5 Industrial Water Use

Industrial water uses for IMC Global, which has an estimated 2001 water use of 2,732 acre-ft/yr (or 890 mgy) is projected to increase annually at a rate of about 0.009 percent. This moderate increase is based on observed increases in water use since the mid 1990s, when IMC Global’s total production was estimated at about 2,620 acre-ft/yr (or 854 mgy).

5.2.6 Total Agricultural Water Use

Current groundwater production for the irrigation of alfalfa and other crops occurs along the northwest portion of the basin near Highway 395 and for various crops and orchards southwest of Ridgecrest. Due to increased controls on water use, groundwater use for agriculture is not anticipated to exceed the current annual rate increase of about 0.01 percent.

5.2.7 Domestic Water Use

To account for a number of small private residential producers in the Indian Wells Valley, aerial photographs, field observations, and other sources were used to obtain a count of wells and residences during 1996. Based on sampling of water usage in the valley, a water duty of 1.2 acre-ft/yr (or 0.39 mgy) per residence was used to estimate residential water usage (EKCRCD 2003). In 1996, approximately 1,440 residences used private wells for domestic and irrigation supply. Therefore, total residential production was estimated at approximately 1,728 acre-ft (or 563 million gallons). The 1996 estimate was projected to increase at a rate of 1 percent to the year 2020.

5.3 DATA LIMITATIONS

Several limitations in the existing data affect the ability to accurately assess the influence of historical pumping on groundwater levels and to obtain accurate estimates of future groundwater use in the Indian Wells Valley. These data limitations include the following:
• Water production estimates for private domestic and agricultural water users are based on assumptions about number of users, crop size and type, and water application. Direct measurement through widespread water metering would provide much more accurate results.

• Likewise, more accurate accounting of current groundwater pumping and water use projections would be possible if more information were available for community (City of Ridgecrest and Inyokern Community Services District) and industrial water supplies.

• There are unknowns concerning demographic trends in the Indian Wells Valley that can significantly impact projections of water use. For example, if the overall base mission and funding levels for NAWS China Lake change as a result of national or global politics, such changes could result in changes in water demands and base groundwater production.

• Changes in land use and zoning throughout the Indian Wells Valley will continue to evolve. Land use and zoning requirements should account for current, projected, and contingency water demands.
6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 INTERPRETATION AND CONCLUSIONS

6.1.1 Hydrogeologic Conceptual Model

The stratigraphy in the Indian Wells Valley is dominated by alluvial and lacustrine sequences that reflect alternating periods of rapid deposition and relatively slow deposition as a result of climatic changes, sediment load to the basin, and active transtensional as well as extensional tectonics accommodating the deposition of sediments. During drier periods when lake levels were lower, basin fill was predominantly alluvial and fluvial sediments, primarily sands and gravels, as sediments were shed from the surrounding Sierra Nevada, Coso, Argus, and southern mountain ranges into the valley and were able to encroach further into the ever widening basin. During periods of increased precipitation and higher lake levels, fluvial and lacustrine processes were dominant. Increased runoff resulted in the development of a larger ancestral China Lake and fluvial processes resulted in the greater influence of deltaic sedimentation both from the Owens River and margin fan-deltas. These deposits are primarily the low-permeability silts and clays.

Historically, two “end member” hydrogeologic conceptual models were hypothesized to describe the regional nature of groundwater flow and recharge and discharge in the Indian Wells Valley: the closed-basin and open-basin models. The differences between the two end member theories are considerable and, therefore, have a significant effect on estimates of the long-term sustainability of the groundwater resource in the Indian Wells Valley.

In the closed-basin model, recharge occurs primarily from precipitation within the topographic drainage basin, occurring along the basin margins, or mountain fronts, through the fan and alluvial deposits at the perimeter of the basin. These deposits are permeable, although the greatest permeability is in the horizontal direction relative to the vertical direction. Consequently, groundwater flows toward the basin lows, the vicinity of the present playas, where it is discharged as a result of pumping or evaporation. Only limited quantities of groundwater recharge or discharge through the surrounding crystalline bedrock joints or fractures is acknowledged. In this model, there must be significant hydraulic interconnectivity between the hydrogeologic zones, as well as upward vertical gradients in zones near the center of the basin, to allow groundwater to move to the surface where it can evaporate. This model assumes that a
significant portion of the basin’s water is retained in the basin, with slow movement to the low point where evaporation is the only significant means of natural discharge.

In the open-basin model, groundwater flow occurs through the basin, interconnecting with adjacent areas. In addition to mountain front recharge along the margins of the basin and limited surface flow, groundwater enters the basin as a result of fracture flow through the crystalline basement complex of the Sierra Nevada and surrounding basin-bounding mountainous areas and leaves the basin through the crystalline basement on the other, downgradient sides of the basin. The open-basin model relies on a significant flux of groundwater being transported into and out of the basin as fracture flow through the surrounding basement complex. Furthermore, upward vertical gradients are not required near the center of the basin and water loss through evaporation constitutes only a fraction of the discharge from the basin.

The estimate of the amount of groundwater withdrawn by pumping in the Indian Wells Valley (about 22,000 acre-ft/yr) is not in dispute and has been quantified to a large degree. However, the amount of water associated with both natural and artificial recharge and discharge from natural sources in the basin has only been estimated, mostly from insufficient data, and with many assumptions that contribute to a large degree of uncertainty (Bean 1989). In the open-basin model, the Indian Wells Valley is thus viewed as a local basin within a larger, regional flow system that includes adjacent areas. The degree of “openness” of the basin is yet to be determined quantitatively.

One of the assumptions of the open-basin model is that groundwater flows through the fractured rock in the mountainous terrain surrounding the basin and that this is a large component of the hydrologic cycle. The isotopic data and the low apparent vertical conductivities through the lacustrine sediments in the central basin suggest that the flow through the surrounding mountains is relatively small, as much of the groundwater in the basin is of late Pleistocene age. Therefore, the groundwater flux through the mountains around the basin may not be nearly as large as hypothesized by some (Thyne and others 1999). The hydrogeologic conceptual model presented in this report falls between the two historical end member models (Figure 6-1). The “either/or” approach must be modified with the realization that the recharge conditions have changed dramatically in the last 14,000 years. The updated hydrogeologic conceptual model incorporates the Pleistocene legacy of a hydrologic basin with both high flux surface and subsurface waters flowing into, through and eventually exiting the basin—all characteristics of an open basin. However, with the advent of the much drier Holocene climate, the Indian Wells Valley groundwater basin has transitioned into a more restrictive basin system having limited recharge, little surface flow, longer groundwater residence times, and less leakage to the adjoining downstream basin.
Water sources and flow paths that were established during the Pleistocene are no longer active but these may still have resulted in preferential pathways. This model recognizes the historical evolution of the basin and has elements of both. Recharge into the Indian Wells Valley comes principally from precipitation in the Sierra Nevada. This Sierra Nevada recharge enters the groundwater system primarily as mountain-front recharge, as infiltration to alluvial aquifers along the margins of the basin, as infiltration through the fractured rock of the adjacent highlands, and through sediments in the ancestral drainage of the Owens River (Little Lake Gap). In this model, some of the groundwater must discharge by moving out of the basin through the surrounding bedrock terrain. The hydrogeologic features represented on Figure 6-1 are simplified to portray this hypothesized groundwater recharge, discharge, and flow direction, showing relative changes in age along groundwater flow paths. Also shown are the effects of pumping and the expected hydrogeologic relationships between the different depositional facies (hydrogeologic zones).

Key elements of this emerging hydrogeologic conceptual model are reflected by the recognition of younger recharge along the Sierra Nevada front from both observed surface and expected fracture flow. Shallow waters from the valley and the few recharge areas sampled are consistently of Holocene (less than 10,000 ybp) age. This is supported by younger water sampled from 27S/38E-13A01. The ages obtained for the deeper waters of the regional aquifer are generally between 10,000 and 40,000 ybp. A few deeper groundwater samples reflect slightly younger ages than would be expected from the stratigraphic depths at which the samples were collected. This likely is a result of younger recharge into these zones. Groundwater in the southwestern Indian Wells Valley is of good quality (Figure 4-2) and may reflect influx of waters from the high Sierra (TtEMI 2003; Thyne and others 2002). A few wells completed in the deeper portion of the regional aquifer indicate the potential for poorer quality waters at depth. Significant drawdown in the regional aquifer is occurring at a rate of 1 to 1.5 feet per year, particularly in the eastern two-thirds of the Indian Wells Valley groundwater basin, and the possibility exists of drawing poorer quality waters from the eastern portion of the basin or deeper zones.

6.1.2 Groundwater Flow Within and Between Hydrogeologic Zones and Basins

Transtensional faulting has been suspected of influencing groundwater flow in the Indian Wells Valley. Many fault traces have historically been considered “barriers” to groundwater flow. However, faulting per se does not appear to have a significant effect on regional groundwater flow in the upper Pleistocene and Holocene sediments of the eastern Indian Wells Valley. Detailed shallow groundwater studies along the fence line area between NAWS China Lake and Ridgecrest suggest that only subtle differences in
Groundwater elevation and geochemistry exist across the Little Lake fault (TtEMI and WGI 2001; TtEMI 2003).

Groundwater flow patterns for the shallow hydrogeologic zone and regional aquifer are discussed in the following subsections. The interpretation presented herein will continue to be refined as more hydrogeologic, water level, velocity, and production well data are acquired and interpreted.

6.1.2.1 Shallow Hydrogeologic Zone

The shallow hydrogeologic zone is composed of Pleistocene and Holocene alluvium. Groundwater within the shallow hydrogeologic zone is discontinuous and generally limited to the eastern and northern portions of the valley, where it is under unconfined, or perched, conditions on top of the low-permeability lacustrine clays of the upper intermediate hydrogeologic zone. The thickness of the shallow hydrogeologic zone ranges from 0 (that is, not present) at the margins of the China Lake playa to approximately 130 feet northeast of the intersection of Inyokern Road and Mahan Street. Groundwater within the shallow hydrogeologic zone occurs under unconfined or water table conditions and generally flows toward the China Lake playa. An exception to this flow pattern occurs in the vicinity of the NAWS China Lake Public Works Compound where a groundwater mound is present.

Water quality within the shallow hydrogeologic zone is highly variable; concentrations of dissolved metals and TDS increase from west to east, with the best quality water noted in the southwest corner of the basin and much poorer quality water near the China Lake playa. Elevated arsenic concentrations are also present in samples from the shallow hydrogeologic zone near the China Lake playa. Stable isotope ratios ($\delta^{18}$O and $\delta^D$) for samples from shallow hydrogeologic zone wells show evaporative enrichment in the heavier isotopes. Young, isotopically heavy groundwater from the shallow hydrogeologic zone represents recharge that infiltrated under the post-Pleistocene climatic regime. $^{14}$C dating of groundwater in the Indian Wells Valley generally shows increasing age with depth.

6.1.2.2 Regional Aquifer

The regional aquifer is primarily composed of coarse sands and gravels with some interbedded lacustrine clays. Groundwater within the regional aquifer may occur under confined, semiconfined, or unconfined conditions. Where the lacustrine clays are present, groundwater is semiconfined to confined. Groundwater conditions become unconfined where these clays pinch out. In general, the regional aquifer is unconfined in the vicinity of Inyokern and in the western- and southernmost portions of Ridgecrest, including the Southwest and Intermediate Well Field areas. In the eastern portion of the valley, the
regional aquifer is confined or semiconfined by lenses of the lacustrine and playa deposits. Water quality is very good for most wells completed in the regional aquifer. Groundwater samples collected in 2002 for the Navy’s basewide study (TtEMI 2003) had TDS concentrations that ranged between 200 and 600 mg/L for monitoring wells that are proximal to the Intermediate Well Field. TDS concentrations increased to the north and east of this region. Pumping of water supply wells has resulted in a cone of depression in the Intermediate Well Field area, which could result in drawing in poorer quality water from the north and east. The development of groundwater resources in areas southwest of the Intermediate Well Field should lessen the likelihood of drawing in the poorer quality water. Stable isotope ratios ($\delta^{18}O$ and $\deltaD$) for groundwater samples collected from wells screened in the deep hydrogeologic zone of the regional aquifer plot close to the global meteoric water line, indicating that little evaporation occurred prior to recharge. Old, isotopically light groundwater represents Pleistocene recharge that infiltrated under cooler climatic conditions and/or at higher elevations.

6.1.3 Interbasin Flow

Fracture flow from the Indian Wells Valley has been speculated to be a primary source of recharge to the Salt Wells Valley since at least 1964 (California Department of Water Resources 1964). Groundwater elevations in the westernmost Salt Wells Valley monitoring wells (TTSWV-MW09 and TTSWV-MW10) are between 175 and 200 feet lower than those in the closest Indian Wells Valley wells (TTIWV-MW09 and TTIWV-MW10), indicating the potential for groundwater flow from the Indian Wells Valley to the Salt Wells Valley (TtEMI 2003). A review of the water quality data supports this hypothesis. This is best exhibited by the Stiff diagrams shown on Figure 4-2. Visually, similar shapes are indicative of similar water quality types (based on relative percentages of the various anions and cations), and total concentrations are represented by size. Therefore, the larger of two similarly shaped Stiff diagrams is indicative of higher concentrations.

The $^{14}C$ data also support the similarity of waters. Samples from wells TTIWV-MW09 and TTIWV-MW10 yielded respective dates of 27,540 and 25,161 ybp, which is the age of shallow water in the clays below the China Lake playa. Water in TTSWV-MW10, completed in crystalline bedrock, has a date of 28,733 ybp. Shallow water in TTSWV-MW09 appears to be derived from older connate water deposited in the upper Salt Wells Valley. As suggestive as the preliminary findings are with regard to confirming flow between basins, future sampling and assessment of detailed water signatures are necessary to confirm hypotheses related to groundwater movement through fractures and between basins.
6.1.4 Sustainability of Groundwater as a Resource

The data clearly indicate that trends in groundwater flow directions and gradients are primarily controlled by seasonal pumping from water supply wells. Secondary influences on the groundwater flow directions and the geometries of the groundwater elevation contours are due to subsurface stratigraphic, sedimentary, and structural features, and to a lesser extent, natural and artificial groundwater recharge. The data set reviewed and reported here provides a more detailed understanding of groundwater flow directions, as well as trends in the relationships among groundwater elevation changes, groundwater flow directions and gradients, and supply well pumping effects.

There has been significant concern regarding the sustainability of groundwater as a resource in the Indian Wells Valley. Groundwater production has decreased from approximately 30,000 acre-ft/yr (or 10,000 mgy) in the mid 1980s to approximately 25,000 acre-ft/yr (or 8,100 mgy) currently. Water level declines in production wells are approximately 1 foot per year. Estimates of overdraft range between 16,000 and 29,000 acre-ft/yr (or 5,200 and 9,500 mgy). The primary limitation on quantifying the amount of overdraft is accurately determining recharge into the basin. Current realistic estimates range between 7,000 acre-ft/yr (or 2,300 mgy) (Krieger & Stewart 1998) and 15,100 acre-ft/yr (or 4,900 mgy) (Bean 1989).

Recharge estimates are complicated by an inability to adequately define the input to the basin that is occurring as fracture flow from beneath the Sierra Nevada to the west. Isotopic analysis results demonstrate that much of the groundwater in the basin is old (greater than 30,000 years) and possibly derived from a source at high elevations, suggesting a possible Sierra Nevada source.

An evaluation of the groundwater data indicates that (1) with the exception of the Armitage Field/China Lake playa study area where there are local upward gradients from the regional aquifer to the shallow hydrogeologic zone, there are area-wide downward vertical gradients between the shallow, intermediate, and deep hydrogeologic zones; and (2) based on a 20-year water level record, groundwater levels appear to be decreasing at a rate of a foot per year, particularly in the central portion of the valley (Intermediate Well Field area).

6.1.5 Beneficial Use

Generally, all waters of the State of California are considered by the State Water Resources Control Board to have beneficial uses, which may include potential use as a source of drinking water, agricultural
supply, or industrial supply. Under the Sources of Drinking Water Policy, all groundwater is considered to be suitable, or potentially suitable, for municipal or domestic water supply, except in cases where the following apply:

- TDS levels exceed 3,000 mg/L (5,000 microSiemens per centimeter of electrical conductivity), and therefore the water could not reasonably be expected by regional boards to supply a public water system.
- There is contamination by natural processes such that the water cannot reasonably be treated for domestic use using either Best Management Practices or best economically achievable treatment practices.
- The water source does not provide sufficient water to supply a single well capable of producing an average, sustained yield of 200 gallons per day.

Under these criteria, groundwater in the Salt Wells Valley does not qualify as having a municipal or domestic beneficial use based on the high naturally occurring TDS concentrations. Additionally, groundwater in portions of the shallow hydrogeologic zone in the immediate vicinity of the China Lake playa also exhibits TDS concentrations in excess of the criterion.

Arsenic must also be considered in the beneficial use context because naturally occurring groundwater concentrations commonly exceed the new federal drinking water standard of 10 µg/L. Many of the wells sampled in the Indian Wells Valley have arsenic concentrations exceeding the 10 µg/L federal drinking water standard that must be met by 2006. As a result, water purveyors must reevaluate their current master planning to determine the applicability and economic effects of the Arsenic Rule from a cost-benefit standpoint.

### 6.2 IDENTIFICATION OF SIGNIFICANT DATA GAPS

The hydrogeologic conceptual model has been developed and refined based upon available data. Considerable information is already in hand regarding the water use history within the valley, general ranges of hydraulic properties of the shallow hydrogeologic zone and regional aquifer, the hydrostratigraphy and structure of the formation materials, and the general water chemistry. In addition, significant information regarding groundwater flow and mixing zones has been gained in recent years through groundwater age-dating and isotope studies. However, several significant data gaps still remain, and the information is considered critical to the overall needs and objectives of the program. Of critical importance is the quantification of safe yield for the Indian Wells Valley groundwater basin. “Safe yield” refers to the rate at which groundwater can be withdrawn without causing a long-term decline of the water
or potentiometric surface (Bouwer 1978). Thus, safe yield is equal to the average replenishment rate of the aquifer. In its broadest sense, safe yield can be considered as the rate at which groundwater can be withdrawn without producing undesirable results (Todd 1959; Bouwer 1978). For the Indian Wells Valley groundwater basin, “undesirable results” include (1) overdraft of groundwater reserves, (2) intrusion of water with increasing concentrations of TDS and trace metals such as arsenic, (3) infringement of competing water rights, (4) loss of community economic development as a result of a shrinking water supply, or (5) the increased potential for land subsidence through tectonic activity such as earthquakes, coupled with pumpage from sands interspersed with high-compressibility clays that could result in compaction of the regional aquifer. Ultimately, the groundwater basin’s safe yield must be quantified to determine how to manage the valley’s groundwater resources over the long term.

The significant data gaps that have been identified in this report can be addressed as follows:

- **Expand the coverage of monitoring points, particularly in the western portion of the valley.** More data points are needed in the western portion of the valley to better refine and quantify our understanding of the significance of recharge entering the western margins of the valley from the Sierra Nevada and to better quantify the safe yield of the groundwater basin.

- **Quantify water level fluctuations and hydraulic properties.** A considerable amount of historical data are already available; however, additional data are necessary to develop a transient hydrologic budget that is defined according to both the effects of groundwater pumping from multiple sources across the basin, as well as the storage capacity and resultant safe yield of the aquifer.

- **Quantify flow between water-bearing zones and groundwater basins.** Additional isotope and age-dating investigations should be conducted to determine the amount of groundwater mixing between hydrogeologic zones and to further define the potential for interflow between groundwater basins, such as the Rose Valley to the north, the Salt Wells Valley to the east, Red Rock Canyon basin to the south, and Sierra Nevada to the west.

- **Quantify storage capacity and safe yield.** New field measurements are needed that can be combined with previously collected data to quantify the storage capacity and safe yield of the regional aquifer through numerical calculations.

- **Quantify watershed recharge.** Various recharge studies have been conducted within the Indian Wells Valley and the associated estimates of recharge amounts obtained from them vary widely. Recharge estimates can be refined through additional monitoring along the western margin of the basin, including direct measurements in the Sierra Nevada drainages and additional groundwater age-dating.

- **Determine applicability and effects of the Arsenic Rule.** The January 21, 2001, Arsenic Rule requires that water systems reevaluate their current master planning to include arsenic treatment that would bring levels down from the previous arsenic concentration standard of 50 µg/L to the new standard of 10 µg/L, achieving compliance by 2006. Samples collected from wells screened...
in the regional aquifer, as part of the Navy’s basewide study, have naturally occurring arsenic concentrations that range from 5 to 61.7 µg/L. Water purveyors need to consider whether it is more cost effective to install arsenic treatment systems at individual well sites or to construct water lines that will convey water systems to a single centralized arsenic treatment facility. Available treatment technologies include ion exchange, activated alumina, reverse osmosis, modified lime softening, electrodialysis reversal, oxidation/filtration, coagulation assisted microfiltration, adsorption using granular ferric hydroxide, or blending water from different sources to achieve the arsenic standard. Alternatively, under the Safe Drinking Water Act, the Environmental Protection Agency will consider exemption to the Arsenic Rule if the following four criteria apply: (1) the public water system is unable to achieve compliance; (2) the system has no reasonable alternative source of drinking water available; (3) the exemption will not result in an unreasonable risk to health; and (4) the system cannot reasonably make management or restructuring changes that would result in compliance or improve the quality of drinking water if compliance cannot be achieved. The Indian Wells Valley Cooperative Groundwater Management Group should collectively review both treatment and exemption options and develop a plan for implementation.

• **Develop cooperative groundwater monitoring and water survey reports.** A Groundwater Monitoring Plan was developed previously by the Kern County Water Agency with review and input by the Indian Wells Valley Cooperative Groundwater Management Group. This plan should be reviewed, revised, and updated to address the data gaps identified in this report. Similarly, groundwater survey reports should be prepared on an annual basis as a cooperative group effort to (1) identify groundwater use and production within the community; (2) present groundwater elevation, flow direction, and water quality data from the monitoring well network established in the Groundwater Monitoring Plan; (3) develop or update hydrographs generated from water level and pressure transducer data; and (4) discuss general water use and water quality trends within the Indian Wells Valley groundwater basin.

Solutions for resolving the data gaps, along with a range of anticipated costs, are provided in Table 6-1. In general, recommended investigations, studies or plans that have potential to fill the greatest number of data gaps should be most strongly considered. Recommended monitoring locations, shown on Figure 6-2, include seven USBR wells (USBR-1, -2, -3, -4, -5, -6 and -10), five IWVWD wells (IWVWD -12, -16, -32, NR-1, and NR-2), and the two Navy Seabee Wells (FRCR01 and SWCB01) located in the El Paso Basin. All or a subset of the recommended monitoring wells should be sampled for inorganic and general chemistry parameters (including major cations, anions, arsenic and other trace metals, and TDS) and target isotopes. In addition, pressure transducers should be installed in these wells to collect continuous water level and temperature measurements. All monitoring wells should be redeveloped prior to water quality and water level monitoring. In addition, canyon monitoring stations should be installed in one or more of the following canyons: Freeman, Indian Wells, Grapevine, Short, Sand, and Nine Mile. The canyon monitoring stations should be equipped with soil moisture monitoring systems coupled with one or more piezometers, a recording stream gage, and a weather station equipped with an evaporation pan, precipitation gage, and anemometer.
Additionally, in October 2002, the EKCRCD, with the support of the Indian Wells Valley Cooperative Groundwater Management Group, submitted an AB 303 grant application for 2003. The purpose of the follow-on grant application is to take the conceptual model developed in this report and to quantify aquifer and watershed parameters within a scientifically and legally defensible framework. Once these parameters are determined or quantified, or a methodology is established for determining those parameters that are subject to variation, a very powerful tool will be available for a variety of applications within the framework of basin-wide best use practices or management of the water resource. The following are among the applications for the outcome of this grant project:

- Determination of recharge to the basin groundwater system
- Determination of “change in storage” of the basin
- Groundwater inflow and outflow characteristics for the basin
- Determination of storage capacity
- Optimization of monitoring plans
- Extent of potential and existing groundwater contamination from human activities
- Suitability of basin for recharge projects
- Optimization of well spacing and pumping capacity
- Continual development of a useable and valid groundwater model
- Use by planners and users for efficient and manageable development of municipal and industrial growth

These applications will form the framework for developing a master plan to optimize the management of the Indian Wells Valley groundwater resources. Optimal yield must be determined by selection of best management practices from a set of possible alternative schemes, as discussed in the following section.

6.3 RECOMMENDATIONS FOR GROUNDWATER PLANNING AND MANAGEMENT

Cooperative planning and management among the various water users needs to continue in the future to develop an optimal water use and development plan that meets the Indian Wells Valley’s current and projected water demands, coupled with the communities’ economic objectives.
6.3.1 Groundwater Planning

Factors to consider in groundwater planning include the following:

- Community involvement is necessary to develop land use planning and zoning requirements that are consistent with the goals and objectives of an optimal water use and development plan.

- Reliability planning is necessary in case of catastrophic water outages that could be caused by water supply shortages resulting from occurrences such as earthquakes, chemical spills, land subsidence, or energy outages. The IWVWD has incorporated reliability planning and an Emergency Action Plan into their 2000 Urban Water Management Plan (IWVWD 2002).

- Data collected during water surveys would be useful in further quantifying groundwater discharge. As part of the Sand Canyon Environmental Education Program, IWVWD distributes water audit kits on an annual basis and the results are collected and stored at IWVWD (2002). The results of these surveys should be considered in future calculations to quantify groundwater discharge. IWVWD water audits and leak detection programs have been enhanced through computer system upgrades so that water consumption can be more accurately monitored. In addition, a meter calibration program system has been implemented so that actual water losses can be more accurately identified and rectified with faster turnaround.

- Public information programs educate residential, commercial, and agricultural water users of ways they can conserve and better manage water. Programs that are currently being implemented include community information on xeriscaping, website access to water use and conservation information, and school education programs such as the Sand Canyon Environmental Education Program. As part of this AB 303 grant, a community outreach program is being identified that includes publicly available information, technical references, and links to Cooperative Groundwater Management Group websites.

It is recommended that the following additional planning activities be implemented:

- An annual water survey report should be developed that reports and updates groundwater production and demands for all water users in the valley. The annual water report should include, but not be limited to, annual meteorological data, water level fluctuation data and other data collected from monitoring stations, water quality data, and information regarding investigations that could tentatively be used to update the hydrogeologic conceptual model or affect other water users in the area. This report should be prepared as a cooperative effort that is based on the findings of each water use group’s annual reporting requirements.

- A basin-wide water-shortage contingency plan should be developed as a cooperative effort among all water use groups. The contingency plan should be updated on an as-needed basis, as identified by the findings of the annual water survey report.

6.3.2 Groundwater Management

Recommendations regarding groundwater management and the development of optimal yield scenarios include the following:
• Limit large scale pumping in areas significantly impacted by declining water levels and water quality and expand into the less developed portions of the Indian Wells Valley.

• Blend groundwater containing low concentrations of TDS with groundwater containing higher concentrations. Consider prior treatment of a portion of the poorer quality water before blending.

• Recycle water through the use of gray water for irrigation, industrial processes, or other established venues.

• Evaluate the importation of water and possible underground injection during the winter months to augment production during the peak summer season.
7.0 REFERENCES


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GLOSSARY OF TERMS

**alkali** any strongly basic substance, such as a hydroxide or carbonate of an alkali metal (e.g., sodium, potassium); *alkali flat* - a level area or plain in an arid or semiarid region, encrusted with alkali salts that became concentrated by evaporation and poor drainage.

**alluvial** formed by the action of running water, as in a stream channel or alluvial fan.

**alluvial fan** a low, outspread, relatively flat to gently sloping mass of loose rock material, shaped like an open fan or a segment of a cone, deposited by a stream (especially in a semiarid region) at the place where it discharges from a narrow mountain valley upon a plain or broad valley; it is steepest near the mouth of the valley where its apex points upstream, and it slopes gently and convexly outward with gradually decreasing gradient. When an alluvial fan enters into a large body of water and becomes partly or totally submerged, the alluvial deposition has many characteristics of a delta and is called a fan-delta.

**alluvium** a general term for clay, silt, sand, gravel, or similar unconsolidated detrital material deposited during comparatively recent geologic time by a stream or other body of running water, as a sorted or semi-sorted sediment in the bed of the stream or on its flood plain or delta, as a cone or fan at the base of a mountain slope; esp. such a deposit of fine-grained texture (silt or silty clay) deposited during time of flood.

**angular** having sharp angles; specifically said of a sedimentary particle showing very little or no evidence of abrasion, with all of its edges and corners sharp.

**anoxic** greatly deficient in oxygen; oxygenless.

**aquifer** a body of rock that is sufficiently permeable to conduct groundwater and yield economically significant quantities of water to wells and springs.

**arkosic** rich in feldspar.

**authigenic** formed or generated in place; specifically said of rock constituents and minerals that have not been transported or that crystallized locally at the spot where they are now found, and of minerals that came into existence at the same time as, or subsequent to, the formation of the rock of which they constitute a part. The term, as used, often refers to a mineral (such as quartz or feldspar) formed after deposition of the original sediment.

**basalt** a general term for dark-colored mafic igneous rocks, commonly extrusive but locally intrusive (e.g., as dikes).

**basement complex** used to describe undifferentiated igneous or metamorphic rocks underlying younger sedimentary rocks.

**batholith** a large, generally discordant plutonic mass that has more than 40 square miles of surface exposure and no known floor.
breccia a coarse-grained clastic rock, composed of angular broken rock fragments held together by a mineral cement or a fine-grained matrix; it differs from conglomerate in that the fragments have sharp edges and unworn corners.

calcareous said of a substance that contains calcium carbonate. When applied to a rock name, it implies that as much as 50 percent of the rock is calcium carbonate.

calcite a common rock-forming mineral: CaCO₃. Calcite is usually white, colorless, or pale shades of gray, yellow, and blue.

caliche a term applied broadly in the southwestern U.S. to a reddish-brown to brownish-yellow or white calcareous material of secondary accumulation, commonly found in layers on or near the surface of stony or sandy soils of arid and semiarid regions, but also occurring as a subsoil deposit in subhumid climates. It is composed largely of crusts of soluble calcium salts, and may occur as a thin porous friable horizon within the soil, but more commonly it is several centimeters to a meter or more in thickness, impermeable, and strongly indurated; the cementing material is essentially calcium carbonate, but it may include magnesium carbonate, silica, or gypsum.

carbonate a sediment formed by the organic or inorganic precipitation from aqueous solution of carbonates of calcium, magnesium, or iron (e.g., limestone, dolomite, and siderite).

clast an individual constituent, grain, or fragment of a sediment or rock produced by the mechanical weathering (disintegration) of a larger rock mass.

clastic pertaining to a rock or sediment composed principally of broken fragments that are derived from preexisting rocks or minerals and that have been transported some distance from their places of origin.

clay a rock or mineral fragment having a diameter less than 1/256 mm (4 microns); a term used in the U.S. and by the International Society of Soil Science for a rock or mineral particle in the soil having a diameter less than 0.002 mm (2 microns). A loose, extremely fine-grained, natural sediment or soft rock composed primarily of clay-size particles and characterized by a considerable content of clay minerals.

coalescing fan one of a series of alluvial fans that flow together to form a bajada.

colluvium mixed and generally chaotic surface deposit on hillsides that moves chiefly by creep or mass wasting down the hillside.

competent applied to rock that under a specific set of conditions is able to support a tectonic force.

conformable said of strata or stratification characterized by an unbroken sequence in which the layers are formed by regular, uninterrupted deposition under the same general conditions. The term is also used to describe the contacts (abrupt, gradational, or intercalated) between such strata. The term is often applied to a later formation having bedding planes that are parallel with those of an earlier formation and
showing an arrangement in which disturbance or erosion did not take place at the locality during deposition.

**conglomerate** a coarse-grained clastic sedimentary rock, composed of rounded to subangular fragments larger than 2 mm in diameter (granules, pebbles, cobbles, boulders) set in a fine-grained matrix of sand or silt, and commonly cemented by calcium carbonate, iron oxide, silica, or hardened clay.

**crystalline** typically used to describe an igneous rock developed through cooling from a molten state and containing no glass, or of a metamorphic rock that has undergone recrystallization as a result of temperature and pressure changes. The term may also be applied to certain sedimentary rocks (such as quartzite, some limestones, evaporites) composed entirely of contiguous crystals.

**delta** a deposit, partly subaerial, built by a river into or against a permanent body of water, resulting in an irregular progradation of the shoreline directly controlled by the river.

**delta front** the uppermost part of the subaqueous delta, seaward of low tide level, and the zone of active river sediment deposition. The delta front is commonly a high energy environment, influenced by waves, currents and tides, resulting in well-sorted, cross-bedded sheet sands.

**delta plain** the level or nearly level surface composing the landward part of a large delta; strictly, an alluvial plain characterized by repeated channel bifurcation and divergence, multiple distributary channels, and interdistributary flood basins.

**desiccate** to dry up.

**desiccation** a complete or nearly complete drying out or drying up.

**detrital** pertaining to or formed from detritus; said esp. of rocks, minerals, and sediments. The term may indicate a source outside the depositional basin or a source within it.

**detritus** a collective term for loose rock and mineral material that is worn off or removed by mechanical means, as by disintegration or abrasion; esp. fragmental material, such as sand, silt, and clay, derived from older rocks and moved from its place of origin.

**diagenesis** all of the chemical, physical, and biological changes undergone by a sediment after its initial deposition, and during and after its lithification, exclusive of surficial alteration (weathering) and metamorphism.

**diatom** a microscopic, single-celled plant that grows in both marine and fresh water. Diatoms secrete walls of silica in a great variety of forms.

**differentiated** said of an igneous intrusion in which more than one rock type developed from a common magma.
dike  a tabular igneous intrusion that cuts across the bedding or foliation of the country rock that is being intruded.

distal  said of a sedimentary deposit consisting of fine clastics and formed farthest from the source area.

embayment  the formation of a bay.

eolation  erosion of land surface by wind driven silt and sand.

ephemeral  short lived.

evaporite  a nonclastic sedimentary rock composed primarily of minerals produced from the evaporation of a saline solution.

evapotranspiration  loss of water from a land area through transpiration of plants and evaporation from the soil and surface-water bodies.

extension  a strain term applied to the lengthening or stretching of large rock units or continental areas by various faulting mechanisms.

extrusive  igneous rock that has been erupted onto the surface of the earth such as lava flows and volcanic ash.

facies  distinct, mappable rock units distinguishable by lithologic, structural, and organic characteristics.

fan-delta  see definition for alluvial fan.

fanglomerate  a sedimentary rock consisting of slightly waterworn, heterogeneous fragments of all sizes, deposited in an alluvial fan and later cemented into a firm rock.

fault  a fracture or a zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture.

fault gouge  soft, un cemented pulverized clayey or claylike material, commonly a mixture of minerals in finely divided form, found along some faults or between the walls of a fault, and filling or partly filling a fault zone; a clay that coats the fault surface, formed by the crushing and grinding of rock material as the fault developed, as well as by subsequent decomposition and alteration caused by underground circulating solutions.

fault, normal  a fault in which the block of rock above the fault (referred to as the hanging wall), appears to have moved downward relative to the block of rock underlying the fault (called the footwall). The angle of the fault is usually 45 to 90 degrees.

fault, strike-slip  (also lateral fault), a fault on which the movement is parallel to the direction in which the fault trends.

fault, thrust  a fault with a dip of 45 degrees or less over much of its extent, on which the hanging wall appears to have moved upward relative to the footwall.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>feldspar</td>
<td>a group of aluminosilicate minerals, which are the most abundant in the earth’s crust. They are commonly light colored, and often have well developed rectangular blocky shapes and well developed cleavage faces.</td>
</tr>
<tr>
<td>felsic</td>
<td>a term applied to igneous rocks having abundant light colored minerals.</td>
</tr>
<tr>
<td>fluvial</td>
<td>of or pertaining to a river or rivers; produced by the action of a stream or river.</td>
</tr>
<tr>
<td>foliation</td>
<td>a general term for a planar arrangement of textural or structural features in any type of rock, especially the planar structure that results from flattening of the constituent grains of a metamorphic rock.</td>
</tr>
<tr>
<td>formation</td>
<td>a body of rock or sediment identified by similar characteristics and stratigraphic position.</td>
</tr>
<tr>
<td>friable</td>
<td>said of a rock or mineral that crumbles naturally or is easily broken, pulverized, or reduced to powder such as a soft or poorly cemented sandstone.</td>
</tr>
<tr>
<td>gastropod</td>
<td>any mollusk belonging to the class Gastropoda, characterized by a distinct head with eyes and tentacles and in most by a single calcareous shell that is closed at the apex, sometimes spiraled, not chambered, and generally asymmetrical, e.g., a snail.</td>
</tr>
<tr>
<td>geothermal</td>
<td>the energy stored as heat within the earth, which can be used as a source of energy. Methods of accessing this energy source involve the flow of hot fluids to the surface, where they can be used as a source of heat or to generate electricity. The fluids may be present naturally near molten rock or they may have to be pumped there.</td>
</tr>
<tr>
<td>granite</td>
<td>a light colored, coarse-grained plutonic rock composed primarily of quartz and alkali feldspar.</td>
</tr>
<tr>
<td>granitic</td>
<td>pertaining to or composed of granite.</td>
</tr>
<tr>
<td>granodiorite</td>
<td>rock that is a diorite with certain granitic characteristics, i.e., with quartz and a certain amount of alkali feldspar.</td>
</tr>
<tr>
<td>gravel</td>
<td>a loose mixture of pebbles and rock fragments coarser than sand; generally considered to have diameters in the range of 2 to 20 mm.</td>
</tr>
<tr>
<td>horst</td>
<td>relatively uplifted crustal unit or block that is bounded by faults on its long sides.</td>
</tr>
<tr>
<td>half-graben</td>
<td>a depressed block bounded on one side by a fault. It may or may not produce a topographic basin or valley.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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</tr>
<tr>
<td>hydrogeologic conceptual model</td>
<td>a qualitative three-dimensional characterization of the interrelationship of the geology, hydrogeology, and geochemistry that has been integrated with naturally occurring groundwater flow and soil/water chemistry characteristics and the relative impacts that anthropogenic activity could have on the safe yield of the groundwater basin.</td>
</tr>
<tr>
<td>igneous</td>
<td>said of a rock or mineral solidified from molten or partly molten material.</td>
</tr>
<tr>
<td>impermeable</td>
<td>incapable of transmitting fluids under pressure.</td>
</tr>
<tr>
<td>indurated</td>
<td>said of a rock or soil hardened or consolidated by pressure, cementation, or heat.</td>
</tr>
<tr>
<td>interbed</td>
<td>a bed, typically thin, of one kind of rock material occurring between or alternating with beds of another kind.</td>
</tr>
<tr>
<td>interglaciation</td>
<td>a climatic episode during which the climate was incompatible with the wide extent of glaciers that characterized a glaciation.</td>
</tr>
<tr>
<td>interplaya</td>
<td>between the playas.</td>
</tr>
<tr>
<td>intrusive</td>
<td>of or pertaining to the emplacement of magma or plastic sediment into preexisting host rock.</td>
</tr>
<tr>
<td>isotopic</td>
<td>having to do with radioactive and stable isotopes.</td>
</tr>
<tr>
<td>joint</td>
<td>a surface of fracture or parting in a rock without displacement.</td>
</tr>
<tr>
<td>lacustrine</td>
<td>pertaining to or produced by or formed in a lake or lakes.</td>
</tr>
<tr>
<td>laminate</td>
<td>consisting of or containing laminations.</td>
</tr>
<tr>
<td>laminations</td>
<td>the thinnest recognizable unit layer of original deposition in a sediment or sedimentary rock differing from other layers in color, composition, or particle size. Laminations are commonly 0.05 to 1.00 mm thick.</td>
</tr>
<tr>
<td>lenticular</td>
<td>resembling in shape the cross section of a lens.</td>
</tr>
<tr>
<td>loess</td>
<td>a widespread, homogeneous, commonly nonstratified, porous, friable, slightly coherent, usually highly calcareous, fine-grained windblown dust that forms a blanket deposit consisting predominantly of silt with subordinate grain sizes ranging from clay to fine sand.</td>
</tr>
<tr>
<td>magma</td>
<td>naturally occurring liquid (mobile rock material) generated within the earth, capable of intrusion and/or extrusion from which igneous rocks have been derived by solidification and other processes.</td>
</tr>
<tr>
<td>mafic</td>
<td>an igneous rock composed chiefly of dark colored minerals (a term derived from magnesium plus ferric).</td>
</tr>
<tr>
<td>marl</td>
<td>generally gray earthy deposit consisting chiefly of a mixture of clay and/or silt and impure calcium carbonate formed under freshwater conditions.</td>
</tr>
</tbody>
</table>
mass wasting slow flowage or creep down hillsides of colluvial material caused by intermittent saturation with water, freeze and thaw, rain drop splash, vegetation and tree throw or sheet or surface washing.

metamorphic pertaining to metamorphism.

metamorphism the process of the mineralogical, chemical, and structural adjustment of solid rocks to physical and chemical conditions that have generally been imposed at depth below the surface zones of weathering and cementation, and which differ from the conditions under which the rocks in question originated.

micaceous consisting of, containing, or pertaining to mica.

olivine basalt basalt containing olivine, an olive-green, grayish-green, or brown mineral that is a common rock-forming mineral of basic, ultrabasic, and low-silica igneous rocks.

orogeny the process of formation of mountains; the process by which structures within fold-belt mountainous areas were formed, including thrusting, folding, and faulting in the outer and higher layers, and plastic folding, metamorphism, and plutonism in the inner and deeper layers.

ostracod any aquatic crustacean belonging to the subclass Ostracoda, characterized by a bivalve, generally calcified carapace with a hinge along the dorsal margin. Most ostracods are of microscopic size, although freshwater forms up to 5 mm long and marine forms up to 30 mm long are known.

optimal yield a groundwater management scheme that best meets, or optimizes, a set of economic and/or social objectives associated with the uses to which the water is to be put.

oxidize to alter by the presence of oxygen either from exposure to air or surface water.

paleosoil; paleosol a buried soil horizon of the geologic past.

paraconformity an obscure unconformity on which no erosion surface is discernible.

pegmatitic the texture of an exceptionally coarse-grained crystalline igneous rock.

perched aquifer a discontinuous lens of high-permeability saturated soils overlying a low-permeability clay layer.

permeability the property or capacity of a porous rock, sediment, or soil for transmitting a fluid.

plagioclase a group of feldspar minerals.

playa a dry, vegetation-free, flat area at the lowest part of an undrained desert basin, underlain by stratified clay, silt, or sand.
<table>
<thead>
<tr>
<th>Term</th>
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</tr>
</thead>
<tbody>
<tr>
<td>playa lake</td>
<td>a shallow, intermittent lake in an arid or semiarid region, covering or occupying a playa in the wet season but drying up in summer; an ephemeral lake that upon evaporation leaves or forms a playa.</td>
</tr>
<tr>
<td>plutonic</td>
<td>pertaining to igneous rocks formed at great depth; pertaining to rocks formed by any process at great depth.</td>
</tr>
<tr>
<td>pluvial</td>
<td>said of a geologic episode, change, process, deposit, or feature resulting from the action or effects of rain; sometimes includes the fluvial action of rainwater flowing in a stream channel; a climate characterized by relatively high precipitation.</td>
</tr>
<tr>
<td>porosity</td>
<td>the porosity between the grains or particles of a rock.</td>
</tr>
<tr>
<td>intergranular</td>
<td>the porosity within the grains or minerals of a rock.</td>
</tr>
<tr>
<td>porosity</td>
<td>the porosity between the grains or particles of a rock.</td>
</tr>
<tr>
<td>intragranular</td>
<td>the porosity within the grains or minerals of a rock.</td>
</tr>
<tr>
<td>porphyritic</td>
<td>the texture of an igneous rock in which larger crystals are set in a finer-grained groundmass, which may be crystalline, glassy, or both.</td>
</tr>
<tr>
<td>postdepositional</td>
<td>after the deposition of a sediment.</td>
</tr>
<tr>
<td>pyroclastic</td>
<td>pertaining to clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin; not synonymous with “volcanic.”</td>
</tr>
<tr>
<td>regression</td>
<td>gradual contraction of a shallow water body resulting in the emergence of land, as when the water level falls or the land rises.</td>
</tr>
<tr>
<td>right-lateral fault</td>
<td>also dextral fault; a fault on which the displacement is to the right when viewed across the fault.</td>
</tr>
<tr>
<td>rock flour</td>
<td>finely ground, chemically unweathered material, consisting of silt- and clay-sized angular particles of rock-forming minerals, chiefly quartz, formed when rock fragments are pulverized while being transported or are crushed by the weight of overlying material.</td>
</tr>
<tr>
<td>safe yield</td>
<td>the rate at which groundwater can be withdrawn without causing a long-term decline of the water table or potentiometric surface.</td>
</tr>
<tr>
<td>sag pond</td>
<td>structurally controlled basin causing water to pond.</td>
</tr>
<tr>
<td>sand</td>
<td>a rock fragment or detrital particle smaller than a granule and larger than a coarse silt grain, having a diameter in the range of 1/16 to 2 mm, being somewhat rounded by abrasion during transport.</td>
</tr>
<tr>
<td>shear</td>
<td>a deformation resulting from stresses that cause or tend to cause contiguous parts of a rock or sediment body to separate sharply.</td>
</tr>
</tbody>
</table>
shell hash  a sediment layer composed of coquina, a detrital limestone composed wholly or chiefly of mechanically sorted fossil debris that experienced abrasion and transport before reaching the depositional site and that is weakly to moderately cemented but not completely indurated; esp. a porous light-colored limestone made up of loosely aggregated shells and shell fragments.

sill  a rise separating a partially closed basin from another basin.

silt  a rock fragment or detrital particle having a diameter in the range of 1/256 to 1/16 mm, being somewhat rounded by abrasion during transport.

slickenside  a polished and smoothly striated surface that results from friction along a fault plane.

sorption  the process of taking up and holding a substance by absorption or adsorption.

splay  one of a series of minor faults at the extremities of a major fault.

strand  the land bordering any large body of water; shore, beach; strand line is the topographic contour of the beach lineament.

stratification  the formation, accumulation, or deposition of material in layers; specifically, the arrangement or disposition of sedimentary rocks in strata.

strike  the direction or trend taken by a structural surface.

strike-slip fault  a fault on which the displacement is to the right on the side opposite the observer.

stringers  a thin sedimentary bed; a mineral veinlet or filament, usually one of a number, occurring in a discontinuous subparallel pattern in host rock.

subangular  somewhat angular, free from sharp angles but not smoothly rounded.

subaqueous  under water.

subaerial  exposed to air.

surficial  pertaining to or occurring on a surface.

syntectonic  said of a geologic process or event occurring during any kind of tectonic activity; or of a rock or feature so formed.

tectonic  said of or pertaining to the forces involved in or the resulting structures or features of the movement of larger structural features of the earth’s crust.

terrigenous  derived from the land or continent.

tonalite  in the International Union of Geological Sciences classification, a plutonic rock with quartz between 20 and 60 percent, and plagioclase/(A+P) greater than 90 percent.
<table>
<thead>
<tr>
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</tr>
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<tbody>
<tr>
<td>transtensional</td>
<td>crustal or rock deformation in oblique directions combining the two elements of extension and strike-slip movement.</td>
</tr>
<tr>
<td>travertine</td>
<td>a finely crystalline, massive deposit of calcium carbonate, formed by precipitation from solution in surface and groundwaters, especially around hot springs, and in limestone caves.</td>
</tr>
<tr>
<td>tufa</td>
<td>a chemical sedimentary rock composed of calcium carbonate, formed by evaporation as a thin, surficial, soft, spongy, cellular or porous, semifriable incrustation around the mouth of a hot or cold calcareous spring or seep, or along a stream carrying calcium carbonate in solution, and exceptionally as a thick, bulbous, concretionary or compact deposit in a lake or along its shore. It may also be precipitated by algae or bacteria. The hard, dense variety is travertine.</td>
</tr>
<tr>
<td>unconformity</td>
<td>a break or gap in the geologic rock or sediment record.</td>
</tr>
<tr>
<td>unconsolidated</td>
<td>said of sediment that is loosely arranged or unstratified, or whose particles are not cemented together, occurring either at the surface or at depth.</td>
</tr>
<tr>
<td>vadose zone</td>
<td>used to describe the unsaturated zone between the ground surface and the top of the water table.</td>
</tr>
<tr>
<td>varve</td>
<td>a sedimentary bed or lamina or sequence of laminae deposited in a body of still water within one seasonal cycle; specifically, a thin pair of graded glaciolacustrine layers seasonally deposited, usually by meltwater streams, in a glacial lake or other body of still water in front of a glacier. A glacial varve normally includes a lower “summer” layer consisting of relatively coarse-grained, light-colored sediment (usually sand or silt) produced by rapid melting of ice in the warmer months, which grades upward into a thinner “winter” layer, consisting of very fine-grained (clayey), often organic, dark sediment slowly deposited from suspension in quiet water while the streams were ice-bound; any cyclic sedimentary couplet, as in certain shales and evaporites.</td>
</tr>
</tbody>
</table>
APPENDIX B

GROUNDWATER ELEVATION CONTOUR MAPS
FOR THE REGIONAL AQUIFER
1995 – 2000
APPENDIX C

DEPTHS TO GROUNDWATER FOR
THE REGIONAL AQUIFER
1995 – 2000
APPENDIX D

HYDROGRAPHS
APPENDIX E

INDIAN WELLS VALLEY GROUNDWATER QUALITY
TOTAL DISSOLVED SOLIDS
JULY 1995