Final Report

Hydrogeologic Investigation of Camp Cady Wildlife Area Newberry Springs, CA

California Department of Fish and Game

and

Mojave Water Agency

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1 INTRODUCTION

1.1 Background

Camp Cady Wildlife Area (Camp Cady) is a 1,866-acre protected wildlife area located 20 miles east of Barstow in San Bernardino County (**Figure 1**). Situated on a former military post established in 1860 on the Old Government Road to Fort Mojave, Camp Cady lies along one of the few reaches of the Mojave River where perennial flows have occurred. These perennial flows (and local shallow groundwater) have historically supported riparian vegetation, including native cottonwood and willow trees, screwbean mesquite, saltgrass, and saltbush, vital to the survival of many desert wildlife species.

In 1979, the California Department of Fish and Game (CDFG) purchased most of the land comprising Camp Cady to protect, preserve, and enhance its unique ecology (additional property west of Harvard Road was purchased in 2001). Over the past 30 years, declining groundwater levels have threatened native riparian habitat at Camp Cady. Historical aerial photographs reveal a dramatic transition from dense riparian stands to increasingly barren swaths and the replacement of diverse native communities by invasive tamarisk (salt cedar) starting in the early 1980s. Perennial flows are reported to have ceased by the mid-1980s. These changes have been generally attributed to local groundwater level declines. However, the timing, location, and degree of riparian habitat loss points to a dynamic and complex relationship between the biological, surface water, and groundwater systems at Camp Cady and the impacts from basin-wide land use changes, recent flooding, and wildfires.

CDFG has engaged in numerous activities to protect and enhance native riparian habitat at Camp Cady, including the removal of salt cedar in the main channel, re-establishment of native vegetation, and operation of two onsite ponds for habitat restoration near the main Ranch house. CDFG has commissioned this study to document how varying climatic, hydrogeologic, and land use conditions have impacted native riparian habitat over time and to evaluate the feasibility of restoring lost habitat in the main channel through an engineered solution involving re-planting and irrigation with local groundwater. This study is being conducted in cooperation with the Mojave Water Agency (MWA) and is funded through the Biological Resources Trust Fund established by the 1996 Mojave River Basin Adjudication.

1.2 Institutional Background

As mandated in the Final Judgment on the Mojave Basin Area Adjudication (Judgment) (Mojave Basin Area Judgment, 1996), MWA was appointed as the Mojave Basin Area Watermaster (Watermaster) and tasked with the responsibility to secure and deliver supplemental water to ensure sustainable and equitable use of water supplies in the Basin. Additionally, MWA is required by the Judgment to collect a Biological Resources Assessment, establish a Biological Resources Trust Fund, and make the Trust Fund money available to the CDFG for the benefit of the riparian habitat areas and species identified in the Judgment. The Trust Fund is derived from a levy of $0.50 (in 1993 dollars) per acre-foot (AF) of groundwater pumped. The Biological Resources Assessment is not levied when the Biological Trust Fund exceeds $1,000,000 (CDFG, 2004). Exhibit H of the Judgment defines the protected riparian areas to be maintained in the Mojave River floodplain, which includes the Camp Cady Wildlife Area.

1.3 Hydrogeologic Setting

Camp Cady is located in the lower portion of the Mojave River Groundwater Basin and is included within the Baja Subarea (Mojave Basin Area Judgment, 1996) (Figure 1). The area is surrounded by the Cady Mountains to the east, Calico Mountains and Alvord mountains to the north/northwest, and Newberry Mountains to the south. As shown on Figure 2, the region is tectonically active and characterized by numerous geologic faults, many of which represent partial barriers to groundwater flow. Key faults include the Camp Rock-Harper Lake (Waterman) Fault, which represents the boundary between the Centro Subarea and Baja subareas, and the Calico Fault, Manix Fault, and Newberry Fracture Zone within the Baja Subarea.

Consolidated, pre-Tertiary rocks, consisting primarily of Mesozoic granitic rocks and Tertiary un-metamorphosed volcanic rocks, comprise the bedrock underlying the basin fill deposits in the Baja Subarea. Available geologic and geophysical logs indicate that depth to bedrock beneath Camp Cady varies considerably, ranging from less than 200 feet along the eastern property boundary (near the outcropping bedrock that forms the Cady Mountains) to at least 700 feet along the western property boundary. Basin fill deposits are comprised of Tertiary and Quaternary alluvial, fluvial, and lacustrine deposits, including interbedded layers of unconsolidated sand, silt, and clay. Unconsolidated basin fill deposits have been delineated into two aquifer systems by the U.S. Geological Survey (USGS): the Regional Aquifer and the Floodplain Aquifer (Stamos et al., 2001). Alluvial deposits of Holocene to late Piocene age form the Regional Aquifer, which uncomformably underlies and surrounds Holocene to Pleistocene fluvial/alluvial deposits of the Floodplain Aquifer throughout the Mojave River Basin (Stamos et al., 2001).

Figure 3 shows a schematic hydrogeologic cross section of the Baja Subarea oriented along the Mojave River extending from the Camp Rock-Harper Lake (Waterman) Fault in the west through Camp Cady to the east (the cross section location is shown on Figure 2). The figure illustrates the hydraulic relationship between the Mojave River and the groundwater system in the Baja Subarea, key aspects of which are described below.

Streamflow losses from the Mojave River represent the primary source of groundwater recharge in the Baja Subarea. Evaluation of gaged flows from 1931 to 2009 at Barstow and Afton indicates that stormflow has reached Camp Cady on average one in every four years, with average annual recharge from streamflow losses in the Baja Subarea estimated at about 7,000 AFY. Other sources of recharge include subsurface inflow from the Centro Subarea across the Waterman Fault and local mountain runoff (Mojave Basin Area Watermaster, 2011 and Stamos et al., 2001).

In the Camp Cady area, the groundwater system is separated into a shallow unconfined aquifer and deeper confined aquifers by the Manix (Clay) Beds. The Manix Beds are Pleistocene lacustrine deposits associated with the ancestral Lake Manix and are comprised of light blue to grey well-bedded clays, silts, and fine sands. The Manix Beds extend from the eastern edge of the Baja Subarea to within three to four miles of the Calico Fault and have a thickness of more than 120 feet beneath Camp Cady. Due to the presence of the Manix Beds, recharge to the deeper aquifer system east of the Calico Fault is limited to the 3- to 4-mile stretch of river west of Harvard Hill.

Groundwater flows east-northeast across the Baja Subarea and exits as baseflow through Afton Canyon. As shown on Figure 3, both the Waterman and Calico faults represent partial barriers to groundwater flow. Groundwater elevations have historically been 40 and 60 feet higher on the western (upgradient) side of the Waterman and Calico faults, respectively. The figure also shows that the slope of the river channel increases east of Mile 15 of the cross section across Camp Cady. This change in slope is physically manifested in the increasing height (relative to the channel) of the northern terraces comprised of exposed Manix Lake Beds from Harvard Hill through Camp Cady into Afton Canyon. The break in channel grade generally coincides with the western extent of the Manix Beds indicating that the main channel was eroded during the drainage of Lake Manix through Afton Canyon. The increase in topographic slope has historically provided flowing artesian conditions in the main channel near Harvard Hill. However, regional groundwater level declines have gradually dewatered the shallow aquifer in the western portion of Camp Cady and shifted the point at which the water table rises to the ground surface in the main channel to the east. Currently, the only areas where depth to water is less than 5 feet below ground surface (feet-bgs) beneath the main channel occurs east of the main Ranch house. As summarized in Section 2 of this report, the timing of groundwater level declines correlates strongly with historical increases in groundwater production in the Baja Subarea as well as with decreased stormflows reaching the Baja Subarea as a result of varying climatic conditions and overproduction in upgradient management subareas.

1.4 Previous Work

This investigation builds on previous work completed by CDFG, MWA, USGS, and others over the past several decades. A landmark study of Camp Cady is the 1989 hydrologic investigation and water use planning study of Camp Cady (Bilhorn, 1989). For that study, detailed topographic surveying and vegetation mapping of the Camp Cady area was performed, and twelve temporary shallow piezometers were installed in the main channel. The temporary shallow piezometers, along with four existing monitoring wells, were monitored over a 14-month period to characterize groundwater levels beneath the main channel and identify potential solutions and physical constraints to restoring riparian habitat in this area. In 1995, average annual ET was estimated to be about 2,000 AFY in the Baja Subarea (Lines and Bilhorn, 1996). The estimate was based on mapping aided by false-color infrared and low-level oblique photographs, vegetation and areal-density classification, and application of representative water-use rates based on selected studies in the southwestern United States. More recently, a study by the U.S. Bureau of Reclamation (USBR) and Utah State University (2011) estimated riparian ET for 2007 and 2010 conditions in the Baja Subarea. The study relied on mapping aided by airborne lidar, multispectral and thermal infrared data, vegetation and surface classification using multispectral imagery, and application of a two-source ET model that considers independent energy fluxes for soil and canopy components. For the Baja Subarea, riparian ET was estimated to be about 2,000 AFY in 2007 and 2,500 AFY 2010 (USBR and USU, 2011). Invasive salt cedar accounted for approximately 35 to 45 percent of total ET in the Baja Subarea. ET estimates cited in the USBR and USU report do not include ET by desert scrub species, which are shallow-rooted and rely on precipitation. The extent of riparian areas along the Mojave River evaluated by Lines and Bilhorn in 1995 and USBR/USU in 2007 and 2010 are relatively similar. However, because of the different methodologies applied, results from the two studies cannot be easily compared to identify changes in riparian ET demand since 1995. Historical aerial photographs were reviewed for this hydrogeologic investigation to evaluate changes in the density and distribution of riparian habitat at Camp Cady over time.

Prior to this study, CDFG and MWA drilled a monitoring well cluster (10N04E19N02-N04) on the north side of the river channel opposite the main Ranch house (see Figure 4 for well location). MWA actively monitors this well cluster and other wells on the north bank of the river. The USGS also monitors water levels in a well cluster on Harvard Road (10N03E27J01-J05) and the domestic supply well at Camp Cady (10N03E25A02). These and other data were incorporated into this study.

1.5 Study Objectives

The primary purpose of this study was to 1) develop a comprehensive understanding of surface water and groundwater dynamics and determine their relationship to the health of riparian vegetation and 2) evaluate the feasibility of developing groundwater resources to re-establish native riparian habitat at Camp Cady. To achieve these objectives, the investigation focused on the following hydrologic and hydrogeologic issues:

1. History of riparian habitat changes at Camp Cady
2. Hydrologic and hydrogeologic conditions at Camp Cady and within the greater Baja Subarea (including the magnitude and duration of intermittent flows in the Mojave River, groundwater production, and groundwater level trends)
3. Current groundwater level conditions and seasonal groundwater level fluctuations beneath and along the banks of the Mojave River
4. Hydraulic connectivity between the shallow and deeper aquifers
5. Hydraulic properties of viable production zone aquifers

1.6 Scope of Work

The scope of work developed for this investigation included the following tasks:

1. Chronicle riparian conditions at Camp Cady through available historical aerial photographs dating back to the 1920s
2. Evaluate the relationship between historical groundwater level trends, groundwater production, and streamflow to identify the key factor(s) controlling riparian health
3. Design and conduct a field investigation program involving a) the drilling and installation of shallow, in-channel piezometers and variable-depth, off-channel monitoring well clusters and b) a formal aquifer pumping test in an onsite production well
4. Incorporate results of the field investigation to refine the conceptual hydrogeologic model of Camp Cady within the context of the greater Baja Subarea

5. Evaluate the feasibility of implementing a riparian restoration program at Camp Cady through an engineered solution involving irrigation with local groundwater

The field investigation task was comprised of the following components:

1. Drill and install eleven shallow piezometers in the main channel of the Mojave River using the hollow-stem auger (HSA) drilling method to characterize groundwater conditions in the shallow aquifer system.
2. Drill and install variable-depth monitoring wells at four locations along the south bank of the Mojave River using the sonic drilling method to characterize groundwater conditions in the shallow and deep aquifer systems.
3. Perform an aquifer pumping test on the existing Camp Cady Pond Production Well (10N03E25A03) to confirm aquifer hydraulic properties and hydraulic connection between the shallow water table aquifer and deeper aquifer units.
4. Professionally survey all monitoring wells installed during the field investigation, the marker at the south end of the Camp Cady bunkhouse, and the 2006 monitoring well cluster (10N04E19N02-N04).

Figure 4 shows the location of the installed shallow piezometers and monitoring well clusters as well as other key wells at Camp Cady. Additional documentation of the field program and new piezometers and cluster wells are provided in appendices to this report. Copies of well drilling permits are provided in Appendix A. Department of Water Resources (DWR) well completion reports for each of the shallow piezometers and cluster monitoring wells are provided in Appendix B. Well logs for shallow piezometers are provided in Appendix C. Selected photographs taken during the field program, as well as historical photographs of Camp Cady during the 2005 flood, are included in Appendix D. The professional as-built survey report showing surveyed elevations of monitoring and production well casings, concrete pads, and ground surfaces are provided in Appendix E.

1.7 Acknowledgements

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2 EVALUATION OF EXISTING DATA

Prior to the field investigation, available groundwater level, production, and streamflow data were evaluated in combination with historical aerial photographs to determine the influence of varying land use and hydrologic conditions on the health of riparian habitat at Camp Cady. This section describes key findings from the evaluation of these existing datasets.

2.1 Groundwater Occurrence and Flow

Current (2010) groundwater elevations in the Baja Subarea range from 2,000 feet above mean sea level (feet msl) at the Centro/Baja subarea boundary to less than 1,600 feet msl one mile east of Camp Cady (Figure 5). In the central portion of the Baja Subarea between Interstate Highways 15 and 40, groundwater levels upgradient (west) of the Calico Fault are at or above 1,770 feet msl, while the groundwater levels over the roughly 5-mile by 5-mile area east (downgradient) of the Calico Fault range from 1,710 to 1,700 feet msl. Groundwater level depressions associated with concentrated pumping are visible at several locations, including the area between Interstate Highways 15 and 40 at Minneola Road, at Harvard Road near the Newberry Fracture Zone, and near Interstate Highway 15 at Harvard Road.

Figure 6 shows groundwater level conditions in the Baja Subarea in 1959. Together, Figures 5 and 6 reveal that groundwater levels in the central portion of the basin from 5 miles west of Minneola Road to Harvard Hill have declined by as much as 80 feet. Along the western boundary of Camp Cady, groundwater levels have dropped by about 60 feet over the past 50 years. The groundwater level contours between the Calico Fault and Camp Cady show that the hydraulic gradient towards Camp Cady has decreased dramatically resulting in a reduction in regional groundwater flow towards Camp Cady.

Figure 7 shows water level hydrographs of selected wells east of the Calico Fault in the vicinity of Camp Cady. Long-term hydrographs are shown from 1930 to present, while more recent data (1990 to present) are highlighted in yellow. This figure shows an average rate of groundwater level decline of about 1.5 feet per year in areas upgradient and south of Camp Cady beginning in the early 1950s. Water levels to the northeast of Camp Cady are more stable as illustrated by the four hydrographs highlighted in yellow on the right side of Figure 7. Additionally, two hydrographs provide information on the vertical hydraulic gradients at Camp Cady. The hydrograph for a USGS monitoring well cluster on Harvard Road (10N03E27J01-05 [highlighted in yellow at the top of Figure 7]) shows that the upward vertical hydraulic gradient at this location in 1992 has gradually shifted to a flat to slightly downward gradient with current depth to groundwater at approximately 50 feet-bgs. Water level measurements at a monitoring well cluster installed by MWA and CDFG in 2006 (10N04E19N02-N04 [highlighted in yellow on the rights side of Figure 7]) indicate relatively stable groundwater levels with a slightly upward vertical gradient. Hydraulic pressure in the deep aquifer zone causes groundwater level to rise just below the ground surface in 10N04E19N02.

2.2 Streamflow

Stream losses from intermittent flow in the Mojave River represent the primary source of groundwater recharge in the Baja Subarea. Stream discharge is controlled by runoff generated from the Mojave River headwaters in the San Bernardino Mountains near Lake Arrowhead (see Figure 1), where annual rainfall averages 41 inches. In contrast, average annual rainfall on the desert floor in the Baja Subarea is less than 5 inches and is subject to high evapotranspiration rates throughout the year. A portion of the runoff generated in the San Bernardino Mountains infiltrates through the floor of the Mojave River recharging the floodplain aquifer prior to reaching the Baja Subarea. Increases in upstream production since the 1950s have further reduced the frequency of low-magnitude stormflows reaching the lower portion of the basin (Lines, 1996).

During wet years with high runoff (i.e., flood years), the Mojave River flows through Barstow and Camp Cady and exits Afton Canyon. The USGS currently monitors streamflow in the main channel at five locations in the basin. Stream gage locations are shown on Figure 1. Figure 8 shows the annual streamflow in the Mojave River measured at the Barstow gage from 1930 to 2009. The figure shows that since 1930 annual discharge at the Barstow gage has averaged 16,377 AFY, of which 14,000 AFY is estimated to enter the Baja Subarea (MWA, 2011). Stormflows have reached Barstow in 23 years of the 80 years on record and have exceeded 90,000 AFY in nine years (corresponding to the flood years of 1937, 1938, 1941, 1943, 1969, 1980, 1983, 1993, and 2005). While the Mojave River Dam in 1971 was constructed to reduce peak flows in the Mojave River downstream of the confluence of its two major tributaries (Deep Creek and West Fork), some of the largest historical mean daily flows at the Barstow gage have been recorded after the dam's construction. As shown below, in each of the nine flood years, the highest recorded mean daily flow rate at the Barstow gage ranged from 2,460 to 18,100 cubic feet per second (cfs), with an average maximum flow rate above 10,000 cfs (photographs of the Camp Cady area taken during the 2005 flood are provided in Appendix D).

Flood Year	**Barstow Maximum Mean Daily Flow (cfs)**
1937	3,030
1938	18,100
1941	2,460
1943	7,380
1969	14,800
1980	8,280
1983	7,520
1993	12,500
2005	16,300
Ave	**10,041**

Also depicted on Figure 8 is the cumulative mean departure (CMD) curve for stream discharge at the Barstow gage (solid red line). The CMD curve represents the cumulative difference (departure) in annual discharge relative to mean annual stream discharge for the period of record from 1930 to 2009 (16,377 AFY) and is a useful method for identifying trends. Positively-sloped sections of the CMD curve represent periods of above-average stream discharge, while negatively-sloped sections of the curve represent periods of below-average stream discharge. The dashed straight red line represents zero departure from the mean, a condition that would result if annual discharge for every year was equal to the mean discharge. The area above the dashed red line represents surplus discharge, while the area below the dashed red line represents deficit discharge. Because the CMD curve is a measure of cumulative conditions relative to the long-term average, the CMD curve begins and ends at zero.

The CMD curve for annual discharge at Barstow indicates that climatic conditions were very wet from 1936 to 1945, resulting in a large surplus in stream discharge. This was followed by an extended dry period that lasted over 20 years until the record flood of 1969. By the end of the dry period, gains in discharge from 1936 to 1945 were effectively erased. Since 1969, four flood years (1980, 1983, 1993, and 2005) have separated periods of little to no discharge. Over the period of record, the frequency and duration of deficit discharge (when the CMD curve is below the zero line) has been low and short, due to the large surplus developed through the mid-1940s (+280,000 AF) and large single-year discharges in more recent times. Overall, it is evident that since the wet period from 1936 to 1945, streamflows reaching the lower portions of the basin have declined.

To assess the influence of historical groundwater production in the upper portions of the basin on the frequency and magnitude of intermittent Mojave River flows and groundwater level declines in the Baja Subarea, the USGS simulated historical conditions with **no** pumping in the upper region of the basin (Alto, Transition Zone, Este, and Oeste subarea) using the Mojave River Basin groundwater model. Simulation results showed that groundwater recharge from the Mojave River in the Baja Subarea increased on average 3,860 AFY over the Base Period (1931 to 1990), but groundwater discharge also increased by 630 AFY. The net effect of the "no upper Basin pumping" scenario was a net decrease in Baja groundwater storage loss amounting to 3,230 AFY. Applying this annual effect to the simulation period from 1931 to 1990 amounts to 193,800 AF of groundwater storage loss in the Baja Subarea due to upper Basin pumping (i.e., in Transition Zone, Alto, Este, Oeste subareas), a significant portion of total groundwater storage losses in the Baja Subarea during the simulation period (Stamos et al., 2001). Changes are attributable to simulated hydraulic heads in the Alto and Transition Zone subareas being near the altitude of the streambed throughout the upper region, which causes potential recharge from the Mojave River to be rejected in the upper region thereby allowing more streamflow to reach and recharge the lower region. The USGS did not simulate the effect of upstream pumping in Centro on stream discharge and recharge in Baja.

2.3 Groundwater Production

Since the early 1950s, the Baja Subarea has been in a state of overdraft as a result of significant increases in groundwater production to support primarily agricultural irrigation in the region. For this study, historical production in the vicinity of Camp Cady and for the greater Baja Subarea was compiled from two sources: 1) estimates of production from 1931 to 1999 incorporated in the USGS Mojave River Basin groundwater model (Stamos et al., 2001), and 2) Mojave Basin Watermaster production records from 1994 to 2009. MWA Wastermater records were determined to be more reliable and used for the six years of data overlap from 1994 to 1999. Figure 9 shows the distribution of groundwater production in the Baja Subarea for selected time periods. Figure 10 shows charts of annual groundwater production within a 2-mile radius of Camp Cady (upper chart), the 0- to 1-mile and 1- to 2-mile radius of Camp Cady (middle chart), and within the greater Baja Subarea (lower chart). As illustrated by the lower chart in the figure, total production in the Baja Subarea exceeds the long-term natural water supply for the Baja Subarea, estimated at 7,400 AFY, starting in the late 1940s (Mojave Basin Area Watermaster, 2011). Subarea production increases dramatically beginning in the mid-1950s and peaks in 1985 at about 59,000 AFY. In the vicinity of Camp Cady, production similarly increased beginning in 1950s through the mid-1960s (upper chart). However, production peaked in 1969 and held relatively constant through 1988, during which average annual production within a 2 mile radius of Camp Cady was 7,730 AFY (upper chart). Separation of pumping into 0- to 1-mile and 1- to 2-mile buffer zones shows that production for the 1- to 2-mile buffer zone surrounding Camp Cady peaked in 1970, while production within a 1 mile radius of Camp Cady did not peak until 1986 (middle chart). With the exception of areas adjacent to the Mojave River that respond directly to intermittent recharge from stream losses, the onset and rate of water level declines across Baja strongly correlate with the timing of increases in groundwater production in the Baja Subarea.

2.4 Historical Land Use and Changes in Riparian Habitat

To document changes in historical land use and distribution of riparian habitat at Camp Cady, aerial photographs dating back to 1929 were obtained from various sources, including the San Bernardino County Flood Control District (SBCFCD) archives, CDFG, Fairchild Aerial Photography Collection, and available public GIS servers. Raw aerial images from the SBCFCD archives were georeferenced in ArcGIS and, together with the other aerial photographs, were used to create a series of maps to chronicle changes in land use and riparian habitat at Camp Cady, as shown on Figures 11 through 24. The dates for which aerial photographs of Camp Cady were available are listed in Table 1 along with the corresponding report figure number.

On each of the figures, locations of key wells, including monitoring wells installed for this investigation, are shown for spatial reference and to aid in describing physical changes observed over time. Based on available historical aerial photographs combined with groundwater level, streamflow, and production data, the following conclusions can be made concerning changes in land use and riparian habitat over time:

- **1929 to 1969.** Perennial flows supporting dense riparian vegetation starting west of Harvard Road and across the entire Camp Cady property is evident in each of the six aerial photographs available for this period. The density of riparian vegetation in the main channel is visibly higher in 1929 and 1955 compared to 1939. It is suspected that the some riparian vegetation was removed by relatively high stream discharge that occurred in 1937 and 1938. Initial clearing for agricultural fields (row crops) north of the main channel near Harvard Road occurs sometime between 1955 and 1962 and south of the river sometime between 1955 and 1964.

- **1969 to 1984.** Over this 15-year period, the western extent of perennial conditions at Camp Cady shifts approximately 3 miles from west of Harvard Road to the location of recently installed piezometer P5. Berms to detain perennial flows and create ponded conditions in the main channel are constructed in the vicinity of P6 and P7 (Figure 17). According to personal accounts, from 1975 to 1985 manual work including digging in the main channel (presumably at the western extent of perennial conditions observed in 1984) and constructed berms provide for perennial conditions in the main channel (personal communication Walt Brock, 2010). Such conditions correlate well with the dewatering of the shallow aquifer and movement of shallow groundwater conditions (less than 5 feet-bgs) to the east. Dense vegetation in the main channel from west of Harvard Road to P3 no longer exists. Local agricultural production increases with four new center-pivot fields on the terrace north of the river and east of Harvard road and additional row-crop fields in the northern floodplain west of Harvard Road.
- **1984 to 1989.** There is no evidence of density contrasts in riparian habitat during this period. However, two new center-pivot fields to the south of Camp Cady east of Harvard Road are evident. In addition, row crops have been converted to a center-pivot field just west of Harvard Road.
- **1989 to 1992.** Some re-establishment of riparian vegetation in the main channel is evident, particularly in barren land near Harvard Road. The type of riparian vegetation cannot be confirmed but is likely salt cedar.
- **1992 to 1993.** A major transition in the main channel from Harvard Road to P5 is evident. Re-established areas from Harvard Road to P4 are now barren. The course of the main channel has turned north between P3 and P4 creating new barren land. Some riparian habitat in the main channel between recently installed piezometers P3 and P5, between P7 and P8, and near P11 has completely disappeared. Water in main channel east of P4 in 1993 (Figure 20) is likely remaining stormflow. Changes over this short period confirm the destructive power of large discharges that occurred in the main channel during the winter floods of 1993.
- **1993 to 2005.** By 2005, center-pivot fields to north are inactive; no more row-crop fields occur north of the river east of Harvard Road. A contiguous area of barren land in the main channel is now visible across the length of Camp Cady. The area is very wide from Harvard Road to P6, narrower from P6 through P8, and widens east of P8. Sand has encroached on the southern portion of the former Hilarides center-pivot field. There is no remaining riparian vegetation along southern margins of the river near Harvard Road. Riparian changes confirm the destructive power of large discharges that occurred in the main channel during the winter floods of 2005. Based on groundwater water level data, the estimated western extent of shallow groundwater has shifted to the vicinity of P4/P5 by 2005.

- **2005 to 2008.** There is no major change in agricultural land use over this period. The impact of two wildfires in August 2005, which burned a total of 670 acres in northern section of river from the area between P4/P5 to Ironwood, is evident. Riparian habitat along southern margins of the river between P9 and P10 has also disappeared. Some speckled regrowth is evident in the main channel (likely salt cedar) between Harvard Road and P4.
- **2008 to 2010.** There are no major changes in land use or riparian conditions over this period. More sand has encroached on the former Hilarides center-pivot field and adjacent lands east of Harvard road. Based on groundwater water level data, the estimated western extent of shallow groundwater has shifted to the vicinity of P6 (Figure 24).

2.5 Conclusions from Evaluation of Existing Data

The evaluation of existing data provides a timeline of biological and land use changes at Camp Cady and reveals the historical sensitivity of riparian health to the gradual dewatering of the shallow aquifer in the western portion of Camp Cady, flooding events, and the 2005 wildfires. Furthermore, the evaluation confirms that riparian habitat was largely unaffected by the extended drought from 1946 to 1968 and flooding prior to the early 1980s due to the protection and re-generative potential afforded by local perennial flows.

These findings provide insight into the future of riparian conditions at Camp Cady should current land use, production, groundwater level, and climatic trends continue. However, in order to evaluate the feasibility of actively restoring and enhancing the existing riparian habitat at Camp Cady, additional data collection was still needed to address the following questions:

1. What are the current groundwater elevations in the shallow and deeper aquifers across Camp Cady?
2. Do flowing artesian conditions still exist at Camp Cady in deeper aquifers underlying the central and eastern portions of the property? If not, is there an upward, flat or downward vertical hydraulic gradient?
3. What is the range of seasonal fluctuations for the water table at Camp Cady?
4. To what extent are the shallow and deep aquifers hydraulically connected/separated?
5. At what scale can deeper aquifers underlying Camp Cady support future riparian restoration projects?

These questions and others helped to focus the scope of the field investigation conducted for this study, details of which are described in the following section.

3 WELL DRILLING, CONSTRUCTION AND DEVELOPMENT

A field program was conducted consisting of 19 exploratory soil borings drilled to depths ranging from 18 to 205 feet-bgs and completed as 2-inch or 2.5-inch diameter PVC groundwater monitoring wells. Monitoring well locations were selected to supplement the existing network of onsite wells and allow for construction of hydrogeologic cross sections along the length of the Camp Cady property. Exploratory drilling and well construction activities, as well as subsurface conditions encountered, are described in this section.

3.1 Pre-Drilling Activities

Prior to field mobilization, a kickoff meeting was held on March 29, 2011 at Camp Cady. Participants included representatives from Todd Engineers (Phyllis Stanin and Edwin Lin), MWA (Lance Eckhart and Anna Garcia), CDFG (Troy Kelly), Tom Bilhorn (consultant to CDFG), Quail Unlimited (Bruce Kenyon), Gregg Drilling and Testing (Don Kirsnis), and Boart Longyear (Mario Romero). During the kickoff meeting, project objectives were discussed, and locations for shallow piezometers and well clusters were selected following visual inspection of primary access ways. During the site visit, it was determined that a formal pumping test of the Camp Cady Pond Production Well (10N03E25A03) would provide aquifer hydraulic data important for identifying potential production zone aquifers. To provide observation wells during the pumping test, one monitoring well cluster (Well Cluster B) was located next to the Pond Production Well.

Following the kickoff meeting, well drilling permits for eleven shallow piezometers and twelve cluster wells were obtained from San Bernardino County Department of Public Health Division of Environmental Health (SBCDPH) on April 5, 2011 (see Appendix A). In addition, Underground Service Alert (USA) was notified, and utilities clearance tickets were obtained on April 7, 2011.

3.2 Technical Approach

3.2.1 Shallow Piezometers

For the shallow piezometers installed in the main channel of the Mojave River, the hollow-stem auger (HSA) drilling method was selected. The HSA method provided a relatively low cost (for shallow drilling and well installation 50 feet or less), clean operation (no drilling fluids used other than water), and ease of transport (light, track-mounted rig and support vehicle).

A linear transect of eleven shallow piezometers in the main channel of the Mojave River was selected to allow for characterization of groundwater conditions along the length of the Camp Cady property to identify favorable reaches for future biological habitat restoration (see Figure 4 for shallow piezometer locations). Shallow piezometers were located along the southern bank of the main channel, as previous studies (Bilhorn, 1989) found no differences in shallow groundwater elevations from north to south within the river bed, and potential locations for habitat restoration on the south bank were identified during the initial site visit. Drilling at each shallow piezometer location was conducted to accommodate the installation of a piezometer in order to 1) monitor the shallow (water table) aquifer, accommodating seasonal and annual groundwater level fluctuations, and 2) identify the vertical thickness of the main channel sand deposits beneath the Mojave River.

3.2.2 Well Clusters

For the cluster monitoring wells, the sonic drilling method was selected. The sonic drilling method is known by several names including Rotasonic, Rotosonic, Sonicore, Vibratory, or Resonant Sonic drilling. Sonic drilling is a dual-cased drilling system that uses high frequency mechanical vibrations to advance flush-threaded steel casing while collecting continuous, relatively undisturbed core samples. Because it does not require the use of downhole drilling muds or other additives, the sonic method also minimizes the time needed for well development.

Similar to the approach used for the shallow piezometer work, a linear transect comprised of four monitoring well clusters along the south bank of the Mojave River was selected to optimize the collection of groundwater level data in shallow and deeper aquifers along the length of the Camp Cady property near areas of historical and existing riparian habitat (see Figure 4 for cluster well locations). Well Cluster B was located adjacent to the Camp Cady Pond Production Well (10N03E25A03) to aid in the collection of hydraulic data during formal pumping tests on this well. Due to the long screen interval in the Pond Production Well (42 to 202 feet-bgs), three wells (shallow, intermediate, and deep) were installed at Well Cluster B. At Well Clusters A and C, no intermediate well was installed to allow for a deeper depth of investigation necessary to penetrate through the Manix Clay Beds and confirm the presence of deeper coarse-grained sediments. No coarse-grained sediments were encountered below the Manix Beds at the Cluster D site, and thus only a shallow monitoring well was installed. Each of the cluster wells is constructed in an independent borehole (i.e., wells are not completed/nested in one borehole).

3.3 Drilling

3.3.1 Shallow Piezometers

On Monday, April 18, 2011, Gregg Drilling and Testing Inc. (Signal Hill, CA) mobilized a track-mounted Marl M5-T (Rhino) limited access hollow stem auger drilling rig and track-mounted (Morooka) support vehicle to the site. Due to extremely high winds and blowing sands on April 18, 2011, exploratory drilling began at Piezometer 6 (P6), the closest location to the ranch house, and proceeded downwind towards P11 (see Figure 4). Upon completion of P11, drilling was continued at P5 and proceeded westerly towards P1. Drilling and well installation time ranged from 1 to 3 hours per well.

All eleven boreholes were drilled using a 6-inch diameter drill bit to accommodate well casing, screen, and artificial filter pack installation. Photographs showing the HSA drilling rig setup and selected samples are provided in Appendix D. During drilling, formation samples collected off the auger flights were examined, described, and archived with the boring designation and depth. No discrete (driven) formation samples were collected during drilling. The depth of the fine-grained deposits encountered near the bottom of each borehole was confirmed based on the combination of clay-rich cuttings brought to the surface on the auger flights, the driller’s observation of the penetration rate, and visual inspection of the deepest auger(s) once removed from the borehole. Well logs for the shallow piezometers are included in Appendix C.

3.3.2 Cluster Wells

On May 22, 2011, Boart-Longyear Drilling Company, Inc. (Upland, CA) mobilized a truck-mounted sonic drill rig and two support vehicles to the site. Initial drilling was conducted on May 23, 2011 at the Cluster B Deep Well, followed by the Cluster B Intermediate Well and Cluster B Shallow Well (see Figure 4). At each well cluster site, geologic cores obtained from the deep exploratory borehole were examined and logged to determine the appropriate design for each well in a cluster. Upon completion of the Cluster B wells, drilling continued in the following order: Cluster A, Cluster C, and Cluster D. Drilling and well installation time to total depth ranged from 2.75 to 3 days for the deep cluster wells, 1.25 days for the intermediate well at Well Cluster B, and 0.5 to 0.75 days for the shallow cluster wells.

All eight exploratory boreholes were drilled by vibrating an 8-inch diameter casing (drill string) into the ground using a sonic drill head to stabilize and hold open the borehole to accommodate well casing, screen, and artificial filter pack installation. During drilling, an inner casing (i.e., 7-inch core casing) was vibrated ahead of the outer casing to collect relatively undisturbed formation cores. At 10-foot intervals, the core barrel was brought up to the surface to retrieve the core sample, which was extruded into Visqueen plastic sleeves. Upon reaching the water table, water was added to the borehole during drilling to minimize heaving of loose, coarse-grained aquifer materials inside the drill casing. During drilling, core samples were examined, described, and archived with the boring designation and depth. Photographs of the sonic drilling rig setup and selected core samples are shown in Appendix D. Hydrogeologic conditions encountered at each of the four well cluster locations are summarized in Section 3.6.

3.4 Well Construction

3.4.1 Shallow Piezometers

Table 2 summarizes the well construction details of the eleven shallow piezometers. Exploratory boreholes ranged from 18 to 50 feet in depth with drilling depths generally increasing from east to west. In each borehole, sediments were comprised primarily of fine to coarse sands with some gravel/cobbles. A stiff silt/clay, representing the top of the eroded Manix Beds, was encountered between 16 and 46 feet-bgs with depths increasing from east to west. All piezometers were constructed to monitor groundwater levels above the top of the silt/clay deposit. Final completion depths ranged from 18 to 43 feet with depths increasing from east to west.

Each well was constructed using 2-inch diameter, flush-threaded, Schedule 40 PVC (2.375-inch outside diameter with wall thickness of 0.154-inch) well casing and 0.020-inch slotted screen. The well screen interval was generally placed just above the contact between the channel sands and clay deposit to maximize the utility of each piezometer should groundwater levels decline in the future and to minimize the potential for vegetative root intrusion. All well screens were wrapped with fiberglass window screen secured with double-locking plastic cable ties prior to installation to minimize the potential of root intrusion. Artificial filter pack material consisted of #2/12 Lupus Lustre Monterey Beach sand. A well seal, consisting of hydrated bentonite pellets, was installed from 5 feet-bgs to the ground surface. The casing for each piezometer was extended to approximately 3 feet above the ground surface and was secured with a threaded brass locking cap (casing stick-up values in Table 2 represent measurements taken in June 2011 after shifting sands raised the elevation of the main channel in some areas). Following the installation of the shallow piezometers DWR well completion reports for the eleven shallow piezometers were filed with SBCDPH and are included in Appendix B.

3.4.2 Cluster Wells

Table 2 summarizes the well construction details of the eight cluster wells. Well profiles are provided on Figures 25 through 28. Final completion depths ranged from 37 to 52 feet for the shallow cluster wells, 109 feet for the Cluster B Intermediate Well, and 184 and 200 feet for the deep cluster wells. Each cluster well was constructed using 2.5-inch diameter, Schedule 80 PVC (2.75-inch outside diameter with wall thickness of 0.276-inch) well casing and 0.020-inch slot screen. The well screen interval was generally placed opposite coarse-grained units. Similar to the shallow piezometers, the well screens in the shallow cluster wells were placed to maximize the utility of each well should groundwater levels decline in the future. Artificial filter pack material consisted of #2/12 graded Monterey Beach sand. In each cluster well, the filter pack extends from the bottom of the borehole to 5 feet above the top of the well screen in all cluster wells. The well seal, consisting of a combination of hydrated bentonite pellets and cement-bentonite grout, was placed above the filter pack in each cluster well. Adequate time for hydration of the pellets was allowed prior to sealing the annulus with cement-bentonite grout to within 2 feet-bgs. A tremie pipe was used to slowly emplace the cement-bentonite grout seal in 20-foot lifts while the drive casing was removed. The riser for each cluster well extends approximately 2.5 feet above ground. Each cluster well was completed at the surface with an 8-inch diameter by 5-foot tall stovepipe well vault with locking lid seated in a 2-foot square by 2-foot thick concrete well pad. DWR well completion reports for the eight cluster wells were filed with SBCDPH and are included in Appendix B.

3.5 Cluster Well Development

Cluster wells were developed from June 7 to June 11, 2011 using a combination of bailing, swabbing, and pumping. Water bailed and pumped from the wells was discharged onsite. A Smeal Rig with a wire-line winch was used to swab the wells using a 2.5-inch diameter surge block. Development water was removed from each well using a 2-inch diameter by 5-foot long PVC bailer. For each well, multiple cycles of swabbing and bailing were performed prior to pumping with a submersible pump. An average of 250-350 gallons of groundwater was removed from each well during well development.

3.6 Hydrogeologic Conditions

Figure 29 shows a hydrogeologic cross section (B-B’) oriented along the Mojave River crossing Camp Cady (cross section location is shown on Figure 4). The cross section includes the well profiles, geologic log, and water levels for each of the shallow piezometers and monitoring well clusters installed for this study and other production and monitoring wells.

The figure indicates that groundwater beneath Camp Cady is hydraulically separated into a shallow unconfined and deep confined aquifer system by the Manix Beds, which consist of clay deposits interbedded with thinner silt/sand lenses. The total thickness of the Manix Beds underlying Camp Cady ranges from approximately 120 to 140 feet. Coarse-grained sand deposits intebeddded with thin silt/clay lenses occur below the Manix Beds at the Cluster A, B, and C sites. At the Cluster D site, sediments encountered below the Manix Beds consist of cemented, friable, and foliated silts/clays mixed with claystone, siltstone, and conglomerate. The cemented and lithified nature of the sediments and the proximity of the Cluster D site to the margins of the basin suggest the presence of a previously unidentified geologic fault.

The lithologies encountered during drilling of the monitoring well clusters along the south bank indicate that clay content in the Manix Beds consistently increases from west to east. As shown on the figure, the color of sedimentary deposits also consistently changes to a dark greenish-gray ("GLEY1" Munsell color code) below an elevation of about 1,620 to 1,640 feet msl at the location of each of the recently installed monitoring well clusters and the 2006 monitoring well cluster on the north bank (10N04E19N02-N04). The dark greenish gray color is indicative of reducing (anaerobic) conditions, suggesting a high degree of aquifer confinement and poor hydraulic connection with the shallow aquifer system. In contrast, the yellowish brown and brownish gray colors generally observed above this elevation indicate oxidizing (aerobic) conditions suggesting relatively good hydraulic communication with the local source of groundwater recharge (Mojave River streamflow). Below the Manix Beds, alluvium (possibly ancestral Mojave River deposits) comprised of fine to coarse sand interbedded with thin silt/clay were encountered at the Cluster A, B, and C locations. The total thickness of coarse-grained deposits beneath the Manix Beds is unknown at each location but, based on estimated bedrock elevations in the region and lithologic distribution in the upper 20 to 30 feet of the formation, is likely to exceed 100 feet. Within the main channel, the thickness of recent coarse-grained Mojave River alluvium ranges from 16 to 46 feet with thicknesses generally decreasing from west to east. The recent alluvium uncomformably overlies the eroded top of the Manix Clay Beds.

Shallow groundwater levels range from approximately 5 to 35 feet-bgs in the main channel from shallow piezometers P1 to P11 with depth to water decreasing from west to east. The saturated thickness of recent Mojave River alluvium in the main channel between P1 and P11 ranges from 10 to 20 feet with an average of about 14 feet. The average depth to groundwater is approximately 6 feet-bgs between P5 and P11. The vertical hydraulic gradient between the shallow unconfined aquifer and deeper confined aquifers is flat to slightly downward along the south bank of the river (from Cluster A in the west to Cluster C in the east) with hydraulic pressures in the deeper aquifer ranging from 17 to 21 feet-bgs. The vertical gradient is slightly upward in the north bank at monitoring well cluster 10N04E19N02-N04, where the potentiometric surface in the deep aquifer zone is just below the ground surface.

3.7 Groundwater Level Fluctuations

Following the completion of the field program in July 2011, MWA staff installed Level TROLL 700, 30 psi gauge pressure transducers and data loggers in each of the eleven shallow piezometers (P1 through P11) and eight cluster wells (A through D) to monitor long-term groundwater levels. Each data logger was set to record water level measurements in 6-hour intervals. Water levels in each piezometer/well from July 2011 through March 2012 are shown on Figure 30. Also shown on the figure are water levels in 10N04E19N02-N04 on the north side of the river channel opposite the main Ranch house. It is noted that the 2010-2011 water year was relatively dry, and winter stormflows generated in the San Bernardino Mountains did not reach Camp Cady during the monitoring period shown on the hydrographs.

The figure shows that water levels in the shallow aquifer of the main channel respond variably from east to west across Camp Cady. From P1 to P5, water levels declined between 2.6 and 4.2 feet over the eight-month monitoring period. The rate of water level decline was less during the winter and spring months presumably due to a decrease in local ET rates of riparian vegetation. Water levels in the shallow aquifer between P6 and P11 declined at a rate similar to those observed in P1 to P5 from July to October 2011 but recovered between 1 and 2 feet from October lows in most wells, with the exception of P6 and P10, which remained relatively stable from October through March. Water level recoveries reflect significant decreases in ET rates of riparian vegetation within and along the main channel east of the main Ranch house.

Water levels in cluster wells A though D responded variably from July 2011 through March 2012. At the Cluster A site, water levels in the shallow aquifer (A-Shallow) declined in a similar fashion as the nearest in-channel piezometer (P4); however static water levels in the deeper confined aquifer (A-Deep) declined more than 5 feet from July through August 2011 and gradually recovered about 4 feet through March 2012. Daily fluctuations indicate that the water levels in the deeper aquifer (A-Deep) respond to pumping of the Camp Cady pond production and domestic supply wells (located near Cluster B on the figure). Over the eight-month monitoring period, the vertical hydraulic gradient at the Cluster A site shifted from a slight downward to slight upward direction.

In the three Cluster B wells, water levels are clearly influenced by pumping of the Camp Cady pond production and domestic supply wells. Static water levels in the shallow aquifer (B-Shallow) declined by about 1 foot over the eight-month period. In contrast, static water levels declined by about 4 feet in B-Intermediate and B-Deep from July through August but mostly recovered by March 2012. The vertical hydraulic gradient varied from slightly upward in July, to downward in August, and back to upward from September 2011 through March 2012.

At the Cluster C site, water levels in the shallow aquifer (C-Shallow) declined by about 2 feet from July to October 2011 and recovered by about 1 foot through March 2012. In contrast, water levels in the deeper aquifer (C-Deep) are more sporadic and appear to respond to local pumping. Static groundwater levels declined by about 1 foot over the eight-month monitoring period. The vertical hydraulic gradient at the Cluster C site was downward throughout the monitoring period.

At the Cluster D site, water levels in the shallow aquifer (D-Shallow) are relatively stable, fluctuating less than 1 foot over the monitoring period.

Overall, seasonal water level trends in shallow piezometers and shallow cluster wells during the 2011-12 monitoring period resembled seasonal fluctuations measured in temporary “in channel” piezometers over a 14-month period for the 1989 Camp Cady Study (Bilhorn, 1989). It is noted that no stormflows from the San Bernardino Mountains reached Camp Cady during the 1988-89 monitoring period. However, water levels rose by 3 to 4 feet from summertime lows in shallow piezometers installed in the main channel west of the main Ranch house during the 1988-89 winter and spring seasons.

4 AQUIFER TESTING

A constant-discharge pumping test was performed on the Camp Cady Pond Production Well (10N03E25A03) to confirm local aquifer hydraulic parameters. This is fundamental to evaluation of the feasibility of developing groundwater resources in deeper aquifers to supply water for future biological restoration projects at Camp Cady. Prior to this investigation, no formal pumping tests have ever been performed on wells in the vicinity of Camp Cady.

The installation of the three Cluster B wells close to the Pond Production Well and subsequent observation of water level drawdown in these wells and other nearby wells (including the inactive Tower Well [10N03E25A01] and the Camp Cady Domestic Production Well [10N03E25A02]) provided the data needed to reliably estimate the transmission and storage capacity of the aquifer, which is a determined by the aquifer transmissivity, horizontal and vertical hydraulic conductivity, and storativity (Figure 4). These parameters were subsequently used to predict the yield and water level drawdown in a future production well tapping the deep aquifer underlying Camp Cady. A three-dimensional numerical groundwater model was developed to evaluate the pumping test results and predict water level response in the shallow aquifer during planned operation of the deep water supply well.

4.1 Technical Approach

The constant-discharge pumping test was conducted on the Pond Production Well using the existing well pump, wellhead appurtenances, and water conveyance system features. The water generated during the pumping tests was discharged through a 4-inch diameter pipe to the fish pond (located nearest to and east of the Ranch house). Discharge rates were controlled with an in-line gate valve, while discharge measurements were recorded with an in-line totalizing flow meter down-stream from the gate value. A newly installed flow meter (McCrometer model M0304) provided both an odometer (cumulative volume) and instantaneous discharge reading from 0 to 800 gpm in 50 gpm increments.

Water levels could not be measured in the Pond Production Well due to insufficient annular space between the 8-inch diameter production well casing and joint fittings on the pump column. Water levels in the three Cluster B wells were monitored at 15 second intervals using a Level TROLL 700, 30 psi gauge pressure transducer and data logger and confirmed with an electric sounder. Water levels in the Tower Well and Domestic Well were measured manually with an electric sounder. The Domestic and Pond Production wells were turned off more than 12 hours prior to testing.

4.2 Well Construction Details

Well 10N03E25A03 (Pond Production Well): This well was installed for CDFG in 1983 by Wallis Water Systems, Inc. (Barstow, CA) using the rotary drilling method. A 15.5-inch diameter exploratory borehole was drilled to a total depth of 210 ft-bgs. The well was constructed with 8-inch diameter steel casing to 202 ft-bgs, and perforated (3/32-inch x 2.5-inch slot size) from 42 to 202 ft-bgs. The well is constructed with artificial filter pack from 20 to 202 ft-bgs and a concrete sanitary seal from 0 to 20 ft-bgs. The depth to water in the well at the time of construction was 28 ft-bgs. In 2005, Eagle Drilling removed the original vertical turbine pump and installed a submersible pump; the intake depth of the submersible pump was set as 110 ft-bgs. This well currently supplies water to the Camp Cady ponds located east of the Ranch house (Figure 4).

Well 10N03E25A02 (Domestic Production Well): This well was installed for Mr. Max Ruderian in 1977 by Howard Pump, Inc. (Barstow, CA) using rotary drilling methods. The 9 7/8-inch diameter exploratory borehole was drilled to a total depth of 80 ft-bgs. The well was constructed with 6-inch diameter steel casing to 80 ft-bgs, and perforated (1/8-inch x 2.5-inch slot size) from 20 to 80 ft-bgs. The well is constructed with artificial filter pack from 20 to 80 ft-bgs and a (concrete?) sanitary seal from 0 to 20 ft-bgs. The depth to water in the well at the time of construction was unknown. This well is located approximately 20 feet southwest of the water tower and serves as the domestic water supply source for Camp Cady.

Well 10N03E25A01 (inactive Tower Well): This well was installed for Mr. Sidney Smith in 1932 for domestic and agricultural uses. The well is located in the water tower and is currently sealed off by a circular steel plate welded onto the top of the casing. The well was constructed with 10-inch diameter steel casing to a depth of 160 ft-bgs. No information on the driller, drilling method, borehole size or depth, and screen interval and screen slot size is available for this well. The depth to water in the well in 1955 was 4.0 ft-bgs, or 0.85 feet above the concrete floor.

Well Cluster B – Deep, Intermediate, and Shallow: Well construction details for the three recently installed monitoring wells are provided in Table 2, and well profiles are shown on **Figure 26**.

4.3 Pumping Test Results and Analysis

On July 13, 2011, an 8-hour, constant-discharge pumping test was conducted on the Pond Production Well. Static water levels for the observation wells, including the three Cluster B monitoring wells, Domestic Well, and Tower Well, were recorded prior to pumping and are provided in Table 3. The Pond Production Well pump was turned on at 6:17 am and turned off at 2:17 pm after 8 hours of uninterrupted discharge. The discharge rate was maintained at 300 gpm for the duration of the pumping test.

Drawdown data for the three Cluster B wells, Domestic Well, and Tower Well are shown on Figure 31. Recovery data are shown on Figures 32 and 33. Water level drawdown and recovery over time were analyzed to estimate aquifer hydraulic parameters including horizontal and vertical hydraulic conductivity and aquifer storage properties in each of the three hydrostratigraphic zones (shallow, intermediate, and deep zones). A combination of classical well hydraulic analytical methods and three-dimensional numerical modeling methods were used to evaluate the data.

4.3.1 Analytical Methods

For the analytical aquifer test evaluation method, drawdown and recovery data for each observation well were plotted on semi-logarithmic charts, and traditional well hydraulic equations (associated with the Cooper-Jacob method) were used to estimate aquifer transmissivity, horizontal hydraulic conductivity, and aquifer storage properties in each of the three hydrostratigraphic zones (Driscoll, 1986). Key details and observations are summarized below.

The measurable drawdown in each of the Cluster B monitoring wells indicates that each of monitored zones contributes water to the Pond Production Well. The relatively straight drawdown curves in each monitoring well also indicate that any vertical leakage between aquifers was minimized by the presence of the Manix Beds, and no firm recharge or discharge boundaries were reached during the test. A slight departure from the straight line curve observed in B-Shallow is likely caused by a combination of local dewatering of the shallow aquifer and/or heterogeneity of shallow deposits. Such uncertainty was addressed by numerical methods. Drawdown and recovery curves have similar straight line slopes and zero-drawdown time intercepts.

In order to estimate aquifer parameters, a method was developed to determine whether the steeper drawdown curves associated with the B-Intermediate and B-Deep wells represented decreasing permeability or increasing water contribution with depth, or a combination of both. The method is summarized in Table 3 and described below. To estimate the relative contribution from the upper, intermediate, and shallow zones during the pumping test, the total thickness of sand deposits opposite the artificial filter pack in each well (20.0 feet for B-Shallow; 12.9 feet for B-Intermediate; and 23.0 feet for B-Deep) was summed (55.9 feet) and divided by the total thickness of sand layers opposite the Pond Production Well screen (98.7 feet) resulting in a ratio of 0.566. Applying this ratio to the discharge rate for the aquifer test (300 gpm) provided a preliminary estimate of 170 gpm that is contributed from the three zones (61 gpm from B-Shallow, 39 gpm from B-Intermediate, and 70 gpm from B-Deep), and 130 gpm that is contributed from unmonitored zones during the pumping test. Respective discharges were applied in the Cooper-Jacob analysis to estimate the aquifer parameters of each zone. The analytical results are summarized in Table 3. The table shows that the estimated transmissivity of the shallow zone is highest (1,262 feet^2/day) followed by the deep zone (536 feet^2/day) and intermediate zone (315 feet^2/day). The estimated transmissivity of the Pond Production Well (3,730 ft^2/day) was calculated by summing the transmissivity values of the three monitored zones and dividing by 0.566. This approach assumes the weighted-average hydraulic conductivity of sand deposits in the monitored versus unmonitored zones is equivalent. The estimated hydraulic conductivity of the shallow zone is highest (63 feet/day) with lower but similar values for the intermediate and deep zones (24 and 23 feet/day, respectively). The aquifer storativitity of the shallow zone was highest (1.09×10^{-3}), followed by B-Intermediate 9.94×10^{-5}, and B-Deep (1.79×10^{-5}), which indicate unconfined conditions in the upper aquifer and increasing aquifer confinement with depth.

4.3.2 Numerical Methods

A three-dimensional transient MODFLOW model was also constructed and used to estimate aquifer hydraulic properties, including vertical hydraulic conductivities and associated leakage between aquifer zones. The model area encompasses an area of 4,000,000 square feet centered around the Pond Production Well. The MODFLOW model comprises 132 rows, 132 columns, and 3 layers representing the shallow, intermediate, and deep aquifer zones. A telescoping finite-difference grid was constructed with small (2-foot) grid cells around the pumping well telescoping to 20-foot cell dimensions for most of the model grid. The transient model simulated the 8-hour constant rate pumping test and a 16-hour recovery period. A total of 72 time steps were used over the 24-hour simulation period. The model was calibrated to the water-level drawdown and recovery in each piezometer and the domestic monitoring well during the pumping test. Both manual and Parameter Estimation (PEST) code calibration simulations were performed. This inverse approach yielded aquifer hydraulic property values for each aquifer zone. The three aquifer zones were modeled as uniform layers with thicknesses based on the total sand thickness opposite each of the Cluster B monitoring wells (20.0 feet for Layer 1, 12.9 feet for Layer 2, and 23.0 feet thick for Layer 3). Inter-lying clay and sand layers between these zones were modeled implicitly using representative (low) vertical hydraulic conductivities. Uniform aquifer hydraulic property values were used for each aquifer zone.

The same flow rate allocations used in the analytical methods for the drawdown and recovery data were used in the MODFLOW model. However, several simulations were performed using different flow allocations based on the results of previous simulations. The final flow allocations are listed in Table 3. The final model calibration indicated that the contribution from the three zones was 40 gpm higher (210 gpm) than estimated using the sand-thickness approach (170 gpm), and that the water pumped from the Pond Production Well was primarily derived from the shallow and deep zones. Several boundary condition configurations were also tested to evaluate model sensitivity to these parameters. Both constant heads and specified (no-flow) flux conditions were simulated. Specified (no-flow) flux conditions resulted in some dewatering of the model domain and incomplete water level recovery during the transient simulations. Constant-head boundary conditions provided better calibration with the observed water level responses to pumping and recovery; therefore constant head boundaries were used in the final calibration runs. Additionally, attempts to simulate leakage from the local ponds indicated that the departure from straight line curve of B-Shallow (Figure 31) is likely caused by local dewatering of the shallow aquifer and due to recharge from the local ponds.

For the MODFLOW model, trial and error calibration simulations were performed initially, followed by PEST autocalibration simulations. For the PEST simulations, horizontal and vertical hydraulic conductivity and specific storage for each of the 3 layers were inverted (allowed to vary during the autocalibration runs) in each of the three model layers. Very good agreement was achieved between observed and simulated water level drawdown and recovery. Figure 34 shows the observed and simulated water level and drawdown results for the three piezometers and the domestic well. As shown in the figure, good agreement was obtained with the calibrated model. Final aquifer hydraulic property values obtained using the calibrated model are listed in Table 3 and summarized on Figure 35. The highest horizontal hydraulic conductivity was estimated for the shallow zone (103 feet/day), with lower but similar values estimated for the intermediate and deep zones (13 and 23 feet/day, respectively). Much lower vertical hydraulic conductivities (less than 0.006 feet/day) were simulated for Layers 1 and 2, consistent with the presence of silt and clay layers logged between the main aquifer zones. Simulated aquifer storage properties indicate semi-confined conditions in the upper aquifer and confined conditions in the intermediate and lower zones. Similar to the approach used in the analytical method, the estimated transmissivity of the Pond Production Well (4,870 feet^2/day) was calculated by summing the individual transmissivity values of the three model sand layers and dividing by 0.566. The estimated transmissivity value is similar to the aquifer transmissivity applied in the USGS groundwater model for the floodplain aquifer outside of the main channel at Camp Cady (1,000 to 2,500 feet^2/day) (Stamos et al., 2001).

5 FEASIBILITY OF RIPARIAN HABITAT RESTORATION

Based on the current understanding of relationships between biological, surface water, and groundwater systems at Camp Cady, it is evident that the successful design of a habitat restoration program involving irrigation with groundwater must consider several factors, including:

- Current and future groundwater levels in the shallow aquifer
- Current and future pathways of major stormflows in the main channel
- Location, well construction, and yield of existing wells
- Potential yield of the deep aquifer
- Distribution and density of existing native and invasive riparian communities

Criteria developed from these factors can be used to identify viable restoration sites, determine the appropriate scale of restoration, and design the facilities needed to pump, store, and convey groundwater to satisfy riparian water demands.

Results of the data review and field investigation indicate that current groundwater conditions in combination with additional pumping from the deep aquifer could support variable-scale riparian habitat restoration projects at Camp Cady. Favorable sites for restoration in the main channel include areas east of the main Ranch house, where the water table occurs within 3 to 8 feet of the ground surface, and along the northern and southern banks that are protected from high-velocity stormflows. Based on the current understanding of the groundwater system, existing infrastructure, and biological objectives, an engineered solution involving planting and irrigation with groundwater may be initially comprised of one or more of the following components:

- A large-scale irrigation project (50 to 200 gpm) requiring the drilling and installation of a new production well tapping the deep aquifer system
- A small-scale irrigation project (5 to 10 gpm) using existing wells on the north bank of the river (see inset on Figure 4)

Potential well yield, associated aquifer hydraulic response, scale of restoration, and preliminary cost estimates for both project types are described below.

5.1 Large-Scale Irrigation Project

Results of the aquifer pumping test on the Pond Production Well can be used to estimate the potential well yield and corresponding water level drawdown in a hypothetical production well tapping the deep aquifer system. Figure 36 shows the predicted water level drawdown for pumping rates ranging from 50 to 200 gpm. The chart shows that the new production well would be capable of providing up to 200 gpm with approximately 70 feet of water level drawdown after 100 days of continuous pumping, a reasonable maximum period of uninterrupted pumping considering downtime for routine well maintenance and variable water demand of native riparian vegetation throughout the year. Drawdown curves assume a 100 percent efficient well, aquifer transmissivity of 1,000 feet^2/day and storativity of

1.7×10^{-4} (equivalent to 50 feet of sand with a hydraulic conductivity and storativity similar to confined sand deposits encountered below the Manix Beds at the Cluster B site).[1]

A preliminary well design for a new production well is shown on Figure 37. The production well is 250 feet deep and is constructed with 8-inch diameter mild-steel casing and screen. Based on the lithology encountered in the deep aquifer system at Cluster Well Sites A, B, and C, a 0.060-inch slotted screen with artificial filter pack (Silica Resources International [SRI] #8 grade sand or similar) is recommended. Modifications to the screen aperture size, screened interval, and filter pack material may be warranted depending on the actual lithologies encountered during drilling.

A 200-gpm well operating 6 months per year produces 161 AF of water. This volume of water could theoretically support a 44-acre, medium-density (40 to 70 percent vegetative cover) community of native cottonwoods and willows, assuming a water usage rate of 3.7 AF/acre (Lines and Bilhorn, 1996). This would cover a square area one-quarter of a mile in length, or roughly the riparian area bounded by Piezometers P8 and P9 and Cluster C (see Figure 4).

Water level response in the shallow aquifer to continuous pumping of the deep aquifer at a rate of 200 gpm was simulated using the three-layer numerical groundwater model. Results indicate that water level drawdown in the shallow aquifer near the new well would likely be minimal (less than 0.3 feet after 100 days) due primarily to the large thickness and low vertical hydraulic conductivity of the Manix Clay Beds. It is noted that simulated water level responses in the shallow aquifer are preliminary and based on key assumptions inherent in the model. Additional evaluation of the influence of constant-head model boundaries and incorporation of intermittent streamflow recharge and varying pumping schedules on shallow aquifer response is needed but beyond the scope of this investigation. For planning purposes, a new production well tapping the deep aquifer would ideally be located close to targeted habitat restoration areas to minimize the cost of water conveyance. However, locating the well some distance away from already established native riparian habitat (e.g., greater than 200 feet) would further reduce the small risk of locally dewatering the shallow aquifer and stressing existing riparian habitat.

A preliminary cost estimate for a large-scale irrigation project is presented in Table 4. As shown in the table, the cost for the drilling, installation, and testing of a new 8-inch diameter production well is approximately $70,000. Currently, because access to electricity across Camp Cady is limited, a solar-powered pump system is assumed for cost estimation purposes. A 50- to 70-gpm solar pump (the highest flowing solar pump on the market) and solar array would cost approximately $16,700, resulting in an estimated total project cost of $86,700. Assuming access to electricity can be provided in the future, we recommend a 4-inch standard electric submersible pump (Grundfos 75S or similar) to allow for a pumping rate up to 100 gpm. For a higher planned pumping rate up to 200 gpm, we recommend a 6-inch diameter standard electric submersible pump (Grundfos 230s or similar).

[1] The storativity (S) of an aquifer is the volume of water released from or taken into storage per unit surface area of aquifer per unit change in water level. For an unconfined aquifer, the S value is referred to as specific yield.

5.2 Small-Scale Irrigation Project

Discussions during the field investigation with Bruce Kenyon, volunteer caretaker at Camp Cady, identified possibilities for small-scale riparian restoration projects on the north side of the river channel. This type of project would involve pumping one or more existing wells on the north side of the main channel at a rate of 5 to 10 gpm, storing water in one or more 550-gallon plastic header tanks, and using either a drip irrigation system or channel lining to distribute the water along natural channels planted with native riparian vegetation.

The location and surface condition of existing inactive wells located along the north bank of Camp Cady were confirmed during the field program (well locations are shown in the inset of Figure 4). There are no records documenting the well construction details of these wells. The following summary is based on field observations and personal communication with Bruce Kenyon (2011). Existing North Well 1 is a former domestic well used historically by CDFG for groundwater level monitoring. The well and screen interval depths are currently unknown; the well is constructed of mild steel, and the top of casing is located at the ground surface. Existing North Well 2 is a former livestock well located adjacent to MWA Monitoring Well 10N04E23M06. The well is constructed with 8-inch diameter mild steel (well depth unknown). The casing stick-up is 1.3 feet, and the current depth to water is 9 feet-bgs. Existing North Well 3 is a 120-foot deep (screen interval is unknown) former domestic well. The well casing is currently covered by a wooden box buried a few feet below shifting sands. The well had been equipped with a solar pump and pumped at a rate of 7 gpm from 2003 to 2005 to irrigate native riparian habitat. The solar pump was destroyed during the August 2005 wildfires at Camp Cady.

A preliminary cost estimate for a small-scale irrigation project is presented in Table 5. As shown in the table, the $5,000 cost estimate covers the costs for a solar pump and solar array system and assumes the use of an existing well on the north bank.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Based on the results of the field investigation, refinement of the conceptual hydrogeologic model for Camp Cady, and estimated irrigation demand to support potential riparian restoration projects, the following conclusions can be made:

6.1.1 Hydrogeologic and Biological Evolution at Camp Cady

1. Under natural (pre-development) conditions, the shallow groundwater table intersected the ground surface of the Mojave River upstream (west) of Camp Cady in the vicinity of Harvard Hill. This topographically-controlled condition provided perennial flows in the main channel at Camp Cady, which supported native riparian vegetation (cottonwood, willow, and mesquite) within and along the banks of the river.

   From the mid-1940s to mid-1970s, overpumping in the Baja Subarea and below-average stormflows in the Mojave River caused groundwater levels to decline at an average rate of approximately 1.5 feet per year across the Baja Subarea. Historical aerial photographs and groundwater level data confirm that stresses on riparian vegetation in the western portion of Camp Cady (near Harvard Road) correlated with local dewatering of the shallow aquifer and migration of the intersection between the shallow groundwater table and ground surface in an easterly direction beginning in the late 1970s.

2. Stressed native riparian vegetation in the main channel both upstream and in the western portion of Camp Cady was removed and transported downstream by stormflows during the 1982-83 flood (and also possibly during the 1979-80 flood). Large areas of previously dense riparian vegetation in the main channel were left barren as a result of flooding.

3. Since the 1982-83 flood, groundwater levels have continued to decline as a result of overproduction in the Baja Subarea. In combination with recent flooding events (e.g., 1994-95, 1997-98, 2004-05, and 2010-11), groundwater declines have further stressed and eliminated riparian vegetation within the main channel and along the banks of the river at Camp Cady in the direction of dewatering in the shallow aquifer system (from west to east).

4. The creation of barren land and migration of dune sands within the main channel upstream of and in the western portion of Camp Cady following the 1982-83 flood is related to declining groundwater levels and destruction of stressed riparian vegetation.

5. Until local and regional groundwater levels can be stabilized, the health of remaining stands of low-density native riparian vegetation within the main channel and along the banks of the river from the

main Ranch house to the eastern boundary of Camp Cady will continue to be at risk to continued dewatering of the shallow aquifer and future flooding.

6.1.2 Current Hydrogeologic Conditions Pertinent to Biological Restoration

1. The shallow groundwater system beneath Camp Cady is supported by the regional (off-river) groundwater elevation and local streamflow losses from the Mojave River.

2. The shallow groundwater system is hydraulically separated from a deep aquifer system by the Manix Clay Beds, an aquitard with an average vertical thickness between 120 and 140 feet.

3. The thickness of recent coarse-grained alluvium in the main channel ranges from 16 to 46 feet with thicknesses generally decreasing from west to east. The recent alluvium uncomformably overlies the eroded top of the Manix Cay Beds.

4. Beneath the Manix Lake Clay Beds exists a deeper aquifer system (>150 feet-bgs) comprised of fine- to coarse-grained sands interbedded with thin clay lenses. This deeper aquifer system does not occur at Cluster Well D (and presumably to the east of Cluster Site D) due to localized faulting. The thickness of the deeper aquifer is unknown; however, depth to bedrock beneath Camp Cady ranges from 200 feet-bgs in the southeast to more than 700 feet-bgs along its western boundary.

5. Historically flowing artesian conditions no longer occur at Camp Cady. Shallow groundwater levels range from approximately 5 to 35 feet-bgs in the main channel from shallow piezometers P1 to P11 with depth to water decreasing from west to east. Depth to groundwater is less than 10 feet-bgs between P5 and P11.

6. Seasonal water level fluctuations from July 2011 through March 2012 range from 2 to 5 feet in most shallow piezometers. Water level fluctuations associated with variable riparian ET demand are more pronounced east of the Camp Cady ranch house.

7. The vertical hydraulic gradient between the shallow unconfined aquifer and deeper confined aquifers is flat to slightly downward along the south bank of the river (from Cluster A in the west to Cluster C in the east) and slightly upward in the north bank at cluster well 10N04E19N02-N04. While the slightly upward vertical gradient may support groundwater levels in the shallow unconfined aquifer in the north bank (by preventing downward vertical leakage), hydraulic heads in the deeper aquifers are too low to provide flowing artesian conditions at Camp Cady.

8. An aquifer pumping test performed on the Camp Cady Pond Production Well confirmed that the deep aquifer system occurs under confined conditions (aquifer storativity = 1.7×10^{-4}) where the Manix Clay Beds are present, and a well tapping deeper sand units similar to those encountered at Cluster Site B (sand hydraulic conducitivity = 23 feet/day) could probably yield 200 gpm with minimal impact to groundwater levels in the shallow aquifer.

9. A preliminary assessment of irrigation demand for native riparian vegetation indicates that an engineered solution involving irrigation with groundwater is feasible and capable of supporting one or more small-scale (5 to 10 gpm) and large-scale (100 to 200 gpm) riparian habitat restoration projects. The preliminary cost estiamte for a large-scale and small-scale irrigation project is about $90,000 and $5,000, respectively. The majority of the cost difference is the drilling and installation of a new 6-inch diameter production well for the large-scale irrigation project.

6.2 Recommendations

Findings from this investigation indicate that available groundwater resources can be developed to support native riparian restoration at Camp Cady involving irrigation with groundwater. We recommend that the following technical guidance be incorporated into a final habitat restoration program:

1. Because riparian vegetation within the main channel will continue to be at risk to declining groundwater levels and future floods, it is recommended that future riparian restoration efforts focus on areas 1) along the margins of the main channel away from high-energy stormflows and 2) between Piezometers P5 and P11, where shallow groundwater occurs less than 10 feet-bgs, providing favorable conditions to successfully re-establish native riparian stands.

2. Of the four cluster sites (A through D) evaluated for this study, Site C appears to provide the most favorable hydrogeologic and biological conditions for habitat restoration. These conditions include 1) good hydraulic separation between the shallow and deep aquifer systems, 2) a shallow water table and flat vertical hydraulic gradient, 3) close proximity to areas in the main channel naturally protected from higher-energy stormflows.

3. For a large-scale riparian restoration project, we recommend the installation of a new production well tapping the deep aquifer system (below the Manix Clay Beds) near areas with historically dense native riparian vegetation (e.g., Cluster C site) but protected from floodwaters. We recommend drilling an exploratory borehole to a depth of at least 250 feet and constructing the well with 8-inch diameter mild steel casing and screen to allow for flexibility in future pumping rates. Based on the lithology encountered in the deep aquifer system at Cluster Well Sites A, B, and C, a 0.060-inch slotted screen with artificial filter pack (Silica Resources International [SRI] #8 grade sand or similar) is recommended. A preliminary 8-inch diameter well design is shown on Figure 37. Modifications to the screen aperture size, screened interval, and filter pack material may be warranted depending on the actual lithologies encountered during drilling.

4. For a planned pumping rate of 100 gpm or less, we recommend a solar submersible pump (Grundfos 4" SQFlex 60 SQF-3); however, the well yield may be limited by the required hydraulic lift to between 50 and 70 gpm. If access to electricity is provided in the future, we recommend a 4-inch diameter standard electric submersible pump (Grundfos 75S or similar) for a pumping rate up to 100

gpm. For a higher pumping rate up to 200 gpm, we recommend a 6-inch diameter standard electric submersible pump (Grundfos 230S or similar).

5. For a small-scale riparian restoration project using one or more existing wells on the north bank, we recommend installing a submersible solar pump (Grunfos 3” 11 SQFlex-2) capable of providing 5-10 gpm. Because construction details (e.g., well and screen interval depths) are unknown for some of the existing north bank wells, we recommend that water level monitoring in all wells on the north bank be conducted at a frequency that ensures early detection of any water level declines in the shallow groundwater caused by pumping.

6. Water levels in the 19 shallow piezometer and cluster wells should continue to be measured with pressure transducers to monitor seasonal fluctuations, responses during storm events, and changes in vertical and horizontal hydraulic gradients.

7. A groundwater quality sample should be collected from one or more of the shallow piezometers (P5 to P11) and deep cluster well (C-Deep) and analyzed for constituents of concern relevant to habitat restoration (e.g., major cations and anions, trace metals, and pH).

7 REFERENCES

ArcGIS (2011) ArcGIS World Imagery - Aerials Express 0.3-meter resolution imagery of Los Angeles, April 9, 2009. http://goto.arcgisonline.com/maps/World_Imagery.

Bilhorn, T. W. (1989) A Hydrology Study and Water Use Plan for The Camp Cady Wildlife Area, San Bernardino County, California, Prepared for California Department of Fish and Game, Contract #FG7504. September 1989, with revisions August 3, 2001.

Brock, W. (2011) Email to Phyllis Stanin, October 19, 2010.

California Department of Fish and Game (2004) Habitat Water Supply Management Plan for the Adjudicated Area of the Mojave River Basin, San Bernardino County, California. July 2004.

California Department of Fish and Game (2011) 1-meter resolution aerial imagery. USDA National Agriculture Imagery Program (NAIP), June 25, 2005 and Summer 2010. http://www.dfg.ca.gov/biogeodata/gis/map_services.asp

Driscoll, F. G. (1986) Groundwater and Wells, 2nd edition. Johnson Division, St Paul, Minnesota.

Kenyon, B. (2011) Conversation with Edwin Lin. June 6, 2011.

Lines, G. C. (1996) Groundwater and Surface-Water Relations Along the Mojave River, Southern California. U.S. Geological Survey Water-Resources Investigations Report 95-4189. Prepared in cooperation with the Mojave Water Agency.

Lines, G. C. and Bilhorn, T. W. (1996) Riparian Vegetation and Its Water Use During 1995 Along the Mojave River, Southern California. USGS Water-Resources Investigations Report 96-4241. Prepared in cooperation with the Mojave Water Agency and California Department of Fish and Game.

Mojave Basin Area Judgment (1996) Judgment After Trial, City of Barstow et al. Vs. City of Adelanto et al. Superior Court Case No. 208568, Riverside County, CA.

Mojave Basin Area Watermaster (2011) 17th Annual Report of the Mojave Basin Area Watermaster, Water Year 2009-2010. May 1, 2011.

Stamos, C. L., Martin, P., Nishikawa, T., and Cox, B. F. (2001) Simulation of Ground-Water Flow in the Mojave River Basin, California. U.S. Geological Survey Water-Resources Investigations Report 01-4002 Version 3. Prepared in cooperation with the Mojave Water Agency.

United States Bureau of Reclamation (USBR) and Utah State University (2011) Evapotranspiration Water Use Analysis of Saltcedar and Other Vegetation in the Mojave River Floodplain, 2007 and 2010. Prepared in cooperation with Mojave Water Agency. August 2011.

University of California Davis Wildlife Health Center (2007) California's Wildlife Action Plan. prepared for California Department of Fish & Game. 1929 Aerial Photograph of Camp Cady. http://www.dfg.ca.gov/wildlife/WAP/report.html

Tables

Figures

Appendix A

Well Drilling Permits

Appendix B

Department of Water Resources (DWR)

Well Completion Reports

Appendix C

Well Logs

for

Shallow Piezometers

Appendix D

Photographs

Appendix E

Merrell Johnson Stamped

As-Built Survey Report