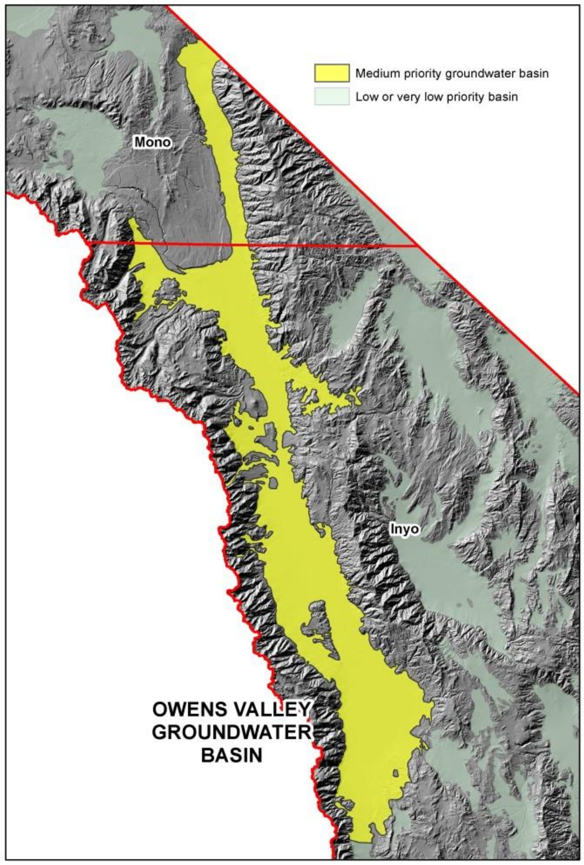
Hydrogeologic Conceptual Model for the Owens Valley Groundwater Basin (6-12), Inyo and Mono Counties



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Robert Harrington, a California Professional Geologist, an employee of Inyo County with expertise in the investigation of water resources and hydrogeology, supervised the preparation of this report titled “Hydrogeologic Conceptual Model of the Owens Valley Groundwater Basin (6-12), Inyo and Mono Counties.”

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Introduction

This report provides a hydrogeologic conceptual model of the Owens Valley Groundwater Basin (OVGB) compiled from numerous sources including the US Geological Survey, Los Angeles Department of Water and Power, Inyo and Mono Counties, the California Department of Fish and Wildlife, and the California Department of Water Resources. Because groundwater and surface water systems are linked, both systems are described here, prefaced by a summary of the physical setting of the OVGB. The report consists of three sections: the first describing general features of the OVGB including physiography, climate, vegetation, and land use; the second section describes the geologic framework of the basin, and the third describes features of the hydrologic system, including the surface water system, and the groundwater system. This report is being submitted to the Department of Water Resources in support of a request from Inyo and Mono counties and the Tri Valley Groundwater Management District of Mono County to subdivide the OVGB into two subbasins, the Tri Valley Groundwater Subbasin and the Owens Valley Groundwater Subbasin; therefore, particular attention is given to the area of the proposed basin subdivision.

Owens Valley Groundwater Basin

<u>Physiography.</u> The OVGB is a 1,037 square mile groundwater basin extending from Haiwee Reservoir on the south, through Owens Valley, Chalfant Valley, Hammil Valley, and Benton Valley to the Nevada state line on the north and includes Round Valley to the west (Figure 1). Chalfant, Hammil, and Benton Valleys form a northern arm of the OVGB referred to as the Tri Valleys area. The OVGB is bounded on the east by the White-Inyo Mountains and Coso Range and on the west by the Sierra Nevada, the Volcanic Tablelands, the Benton Range, and Blind Spring Hill. The northeastern boundary of the OVGB is the Nevada state line. The OVGB occupies the lower elevations of the Owens River watershed, and is characterized by relatively subdued topography of playa, valley floor and alluvial fan surfaces.

The watersheds surrounding the OVGB are characterized by steep mountainous slopes and canyons of the bedrock mountain ranges. Elevations in the OVGB range from below 3,600 feet above mean sea level (amsl) on the Owens Lake playa, to over 9,700 feet amsl in the northwest part of the basin near Basin Mountain. The Sierra Nevada and White-Inyo Mountains rise steeply above the OVGB to elevations over 14,000 amsl. The mountain fronts are flanked by large alluvial fans, which grade into alkali flats, playas, and river flood plains along the axis of the valley. The OVGB is the on the western margin of the Basin and Range Physiographic Province, which is characterized by north-south oriented, elongate fault-bounded valleys separated by rugged mountain ranges.

Note that Figure 1 includes Fish Slough, north of Bishop, within the boundaries of the groundwater basin, but the current Bulletin 118–2003 (DWR, 2003) boundaries do not include Fish Slough in any groundwater basin. Fish Slough was included as an independent groundwater basin in Bulletin 118 (DWR, 1975) and Bulletin 118-80 (DWR, 1980), but dropped from Bulletin 118-2003 (DWR, 2003) on the reasoning that "*Granite Mountain Area (6-59) and Fish Slough Valley (6-60) groundwater basins have been deleted because no information was found concerning wells or groundwater in these basins or because well completion reports indicate that groundwater production is derived from fractured rocks beneath the basin*." Shallow cores from Fish Slough show alluvium is a thin veneer on the order of ten feet atop Bishop Tuff.

<u>Climate.</u> Owens Valley's climate is warm and dry in the summer, and cool and moist in the winter. Precipitation and temperatures are strongly influenced by elevation. In the Owens River watershed, the high elevations of the Sierra Nevada and White-Inyo Range have cooler temperatures and higher precipitation than the valley floor. The Sierra Nevada is oriented roughly perpendicular to the paths of oncoming winter storms, and is on the windward side of the watershed. Moist air masses rise when they encounter the Sierra, the rising air cools, and water vapor condenses and falls as rain or snow. As air masses descend the eastern slope, the descending air warms, clouds evaporate, and precipitation declines east of the range. The combined effect of increased precipitation as air masses ascend the west slope and cross the range crest, and decreasing precipitation as air masses descend the east slope is known as the "rain shadow effect." The highest precipitation rates in the Owens River watershed are in the highest elevations in the Sierra Nevada, occurring as winter snow. Because of the rain shadow

effect, precipitation decreases to the east across the watershed. The rain shadow effect and the effect of topography result in highly variable precipitation in the watershed (Figure 2). Because the groundwater basin occupies the lowest elevation in the watershed, it is characterized by low precipitation (generally between 5 to 10 inches per year on average).

Vegetation. Because much of the land in the OVGB and Owens River watershed is in federal, state, and municipal ownership, native vegetation covers most the area. Vegetation in OVGB varies with elevation, floristic region, soil salinity, and water availability. Vegetation communities range from salt-tolerant shadscale scrub, alkali sink scrub, desert greasewood scrub, alkali meadow, and desert saltbush scrub on the low elevations of the valley floor, to more drought-tolerant Mojave Mixed Woody Scrub, Blackbush Scrub, and Great Basin mixed scrub on alluvial fans (Davis et al., 1998; Howald, 2000). The OVGB lies on the boundary of the Great Basin and Mojave deserts; consequently, the southern part of the OVGB has vegetation communities such as Mojave creosote bush scrub characteristic of the hot Mojave Desert to south and the northern part of the basin has communities such as Big Sagebrush scrub characteristic of the cooler, higher Great Basin Desert. Hydric vegetation communities associated with streams, springs, and wetlands occupy relative small areas of the OVGB, but are important habitat resources. At higher elevations in the watershed, vegetation ranges through Pinyon-Juniper woodland, montane forest and meadow, subalpine forest and meadow, to alpine plants and barren terrain above timberline (Howald, 2000).

In the arid environment of the Owens Valley, vegetation communities are mediated by hydrology. On alluvial fan surfaces, where the water table is disconnected from the root zone, plants subsist on precipitation alone. Near stream channels, ditches, canals, and along the Owens River, surface water supports riparian communities. Areas of shallow groundwater support alkali meadow, alkali sink scrub, shadscale scrub, and desert saltbush scrub communities. Groundwater discharge zones support alkali meadow, phreatophytic scrub communities, transmontane alkali marsh and aquatic habitat.

Land Use. The majority of land in the OVGB is owned by federal, state, or municipal entities (Figure 3). The land uses are grazing, irrigated agriculture (principally alfalfa and other feed crops), and tourism based recreation. Most irrigation and cultivation of crops occurs on lands owned by the City of Los Angeles that are leased to ranchers and farmers. Urban and residential development is concentrated in the City of Bishop, communities west of Bishop, and the towns of Benton, Chalfant Valley, Round Valley, Big Pine, Independence, Lone Pine, Keeler, and Olancha. Population within the OVGB is approximately 14,000.

Geologic Framework

Owens Valley lies at the western edge of the Basin and Range Tectonic Province, and the dramatic topography of the basin is an expression of the underlying tectonic processes. The Basin and Range Province is characterized by north-south oriented mountain ranges and narrow intermountain valleys bounded by normal faults, and the Owens Valley is the westernmost basin in the Province. On the west, the Sierra Nevada consists of uplifted granitic and metamorphic rocks, locally mantled by glacial and volcanic deposits. To the east, the White-Inyo Range consists of Paleozoic sediments, Mesozoic volcanic rocks, and metamorphic rocks that have been folded, faulted, and intruded by granitic plutons, and are locally mantled with Quaternary sediments and Tertiary volcanic rocks. The present topography was produced by extensional faulting that initiated in the Miocene and produced northwest trending faults. A later phase producing north-south trending normal and strike slip faults initiated in the Pliocene or Pleistocene and is still active. The contact between low permeability fault-bounded mountain blocks and more permeable valley-fill material generally forms the bedrock boundaries of groundwater basin; however, the basin boundary west of Chalfant and Hammil valleys is formed by the edge of the surficial expression of the Bishop Tuff, a Pleistocene rhyolitic ignimbrite that overlies basin fill and bedrock.

The Sierra Nevada and the White-Inyo Range were glaciated during the Pleistocene and Holocene. Glaciation was far more extensive in the Sierra Nevada due to its westerly position, proximal to the Pacific Ocean and incoming synoptic scale storms. Glacial moraines extend beyond the range front and into the groundwater basin in the region from Big Pine to Round Valley, contributing material to the alluvial fans flanking the Sierra Nevada (Bateman, 1965).

Owens Valley, and its continuation through Chalfant, Hammil, Benton, and Round Valleys, is formed by subsidence of the valley bottom due to Basin and Range extensional tectonics. As the valley bottom has subsided, the valley-fill has accumulated, consisting mainly of sediment shed from the adjacent mountain blocks, and also volcanic rocks. The sedimentary material consists of unconsolidated to moderately consolidated alluvial fan and glacial moraine deposits adjacent to the mountain range fronts, fluvial plain deposits near the axis of the valley, deltaic deposits, and lacustrine deposits. Older alluvial fan deposits tend to be elevated and at the margins of the valleys (Figure 4). Sediments of the central axis of the valleys are typically fluviolacustrine, playa, and dune deposits. In well logs, valley fill sediments are expressed as sands, gravels, boulders, and clay layers. Sedimentary strata are variable vertically and laterally. Depositional environments change over relatively short distances resulting in laterally discontinuous sand, gravel, and clay lenses. Tectonic activity and climate variations change sediment supply and depositional energy at any given point, resulting in lithologies changing over vertical distances of a few feet to a few dozen feet. Laterally extensive clay strata are present beneath Owens Lake and in the Big Pine area. Owens Lake has expanded and contracted during Pleistocene glacial and interglacial periods, and has at time overtopped the topographic high at the south end of Owens Valley and been hydrologically connected with Searles Lake in Searles Valley and Pleistocene Lake Manly in Death Valley. Owens Lake most recently overflowed into Rose Valley and Indian Wells Valleys to the south about 3 ka.

Volcanic rocks are present as valley fill in the basaltic cinder cones and flows of the Big Pine Volcanic Field south of Big Pine, in small basaltic plugs west of Bishop, and in the northern Owens Valley as Bishop Tuff. Bishop Tuff is a rhyolitic welded tuff erupted from the Long Valley Caldera 767 ka (Crowley et al., 2007), northwest of Owens Valley (Figure 4). Bishop Tuff dominates the land surface north of Bishop and west of Chalfant and Hammil Valleys, and is present at depth well logs in Chalfant Valley, Laws, and Bishop. The Bishop Tuff consists of basal unconsolidated pumice, overlain by a dense heat-welded zone, and a less dense gas welded zone. Where Bishop Tuff forms the groundwater basin boundary west of Chalfant and Hammil valleys, it is likely underlain by valley fill. In the Owens River Gorge, near the northwestern extent of the OVGB, Bishop Tuff is underlain by granitic bedrock. Hollett et al.

(1991) considered that recharge to valley fill was likely to occur where the basal pumice was exposed, and that recharge through the welded zones was unlikely except along faults and fractures.

Basalt flows south of Big Pine emanate from vents along the range front and are interstratified with valley-fill sediments. Basalts between Big Pine and Independence are the highest permeability aquifer materials found in Owens Valley.

Structural geology and basin geometry of the OVGB is dominated by faulting related to regional tectonism, with both normal and strike slip components. Faults at the margins of the basin are generally normal faults with the basin down-dropped relative to the mountain blocks, though locally mountain-downward normal faults also occur, forming minor grabens along the range front. Faults also occur in the valley fill, generally parallel to the axis of the valleys. The Owens Valley Fault extends from Owens Lake to north of Big Pine. The largest recorded earthquake in the Basin and Range Province occurred on the Owens Valley Fault in 1872, with an estimated magnitude of 7.5-7.8, generated by dominantly right-lateral motion. Numerous sag ponds, sand blows, pressure ridges, and other features related to the 1872 event are present along the trace of the fault (Beanland and Clark, 1994; Slemmons et al., 2008). Other faults occur as branches of the range front faults and Owens Valley Fault. A number of springs occur along faults where the faults act as barriers to flow across the fault plane. In the Volcanic Tableland, the Bishop Tuff is broken by many north-south and northwest-southeast oriented fault scarps, the largest of which forms the eastern boundary of Fish Slough, north of Bishop and west of Chalfant Valley.

The bedrock beneath the Owens Valley fill consists of down-dropped fault-bounded blocks at varying depths. Numerous geophysical methods have been used to define the form and depth of the bedrock surface (Pakiser et al., 1964; Danskin, 1998; MWH, 2010; MWH, 2011), which showed that the bedrock beneath the valley is not a single down-dropped block, but rather is a series of deep basins separated by relatively shallow bedrock divides. The deepest part of the basin is beneath Owens Lake and is overlain by over 8,000 feet of valley fill. Another deep basin lies between Bishop and Big Pine, estimated to be more than 4,000 feet deep. Other shallower basins are present east of Lone Pine and beneath Hammil Valley. These basins are separated by blocks of shallower bedrock. Valley-fill strata within the deeper portions of the basin have a "stacked bowl" configuration with the deepest part of each stratigraphic horizon occurring in the deepest part of the basin (e.g., MWH, 2012, Figure 3).

Gravity data indicate bedrock is relatively shallow between Benton and Hammil valleys and between Laws and Chalfant Valley (Pakiser et al., 1964; Hollett et al., 1991). The subsurface bedrock block between Laws and Chalfant Valley affects groundwater flow and is a key geologic feature supporting this request for a groundwater basin boundary revision. The acceleration due to the earth's gravity varies slightly at different locations due to the varying density of rock at depth. Gravitational acceleration is slightly greater at points overlying high density rock than at points overlying less dense rock. Because alluvial basin fill is less dense than typical bedrock types, variations in gravitational acceleration can be used to estimate the depth to bedrock in alluvial basins and other features of the basin geometry. Figure 5a (from Pakiser et al., 1964, combined Plate 1, Sheets 1 and 2) shows gravity contours that delineate the subsurface barrier deflecting groundwater west into the Fish Slough area where it discharges along the Fish Slough fault.

Hydrologic System

Much of the land and the majority of water rights in Owens Valley are owned by the City of Los Angeles for the purpose of exporting water from the eastern Sierra to Los Angeles (Figure 3). Los Angeles has developed extensive facilities for water storage and export, land and water management, groundwater production, groundwater recharge, surface water and groundwater monitoring, and dust control. Because of the importance of water supplied from Owens Valley to Los Angeles, Los Angeles water monitoring is extensive and considerable study has been devoted to Owens Valley hydrology. Because Los Angeles owns relatively little land in Chalfant, Hammil, and Benton valleys, they are less studied and monitoring is sparse compared to Owens Valley.

<u>Surface Water System.</u> The primary surface water features in the OVGB are the Owens River and its tributaries draining the eastern slope of the Sierra Nevada. The Owens River flows from

Long Valley, northwest of the OVGB, into Owens Valley and south along the axis of the valley. Streams draining the high elevations of the east slope of the Sierra Nevada join either the Owens River or are diverted into the Los Angeles Aqueduct (LAA). Like many watersheds in the Basin and Range Province, the Owens Valley is internally drained, with the natural terminus of the watershed at Owens Lake. Owens Lake dried up in the 1920s due to upstream diversions of the Owens River and its tributaries. Flow in the Owens River is controlled by a series of reservoirs operated by Los Angeles Department of Water and Power (LADWP) and Southern California Edison Corporation (SCE). Flow in the Owens River is supplemented near its headwaters by diversions through the Mono Craters Tunnel from the Mono Basin. Water-year releases from Pleasant Valley Reservoir, where the Owens River enters the OVGB, averaged 258,000 acre-feet per year (AFY) and ranged from 109,000 to 444,000 AFY during the period 1959-2014. The Owens River's natural terminus was Owens Lake prior to completion of the LAA in 1913. As a result of diversions from the Owens River and its tributaries, Owens Lake was dry by the 1920s. Beginning in 2002, Los Angeles has operated a dust control project on the Owens Lake lakebed, using up to 75,000 AFY to control dust emissions. Since 2006, LADWP and Inyo County have initiated a mitigation project to reintroduce a 40 cubic feet per second (cfs) flow into the channel of the Owens River below the LAA intake. When this flow reaches the Owens Lake delta, it is either used on Owens Lake for dust control or pumped back to the LAA.

Numerous tributary streams drain the east slope of the Sierra Nevada either join the river or are diverted into the LAA. The largest of these, Bishop Creek, has an annual average discharge of 75,000 AFY and ranged from 37,000 to 134,000 AFY during the period 1909-2014.

There is no direct surface water connection between the Tri Valleys and the Owens River. An ephemeral wash occiasionally flows from Chalfant into the Laws area during extreme precipitation events. During Pleistocene glacial periods, Mono Lake overtopped its basin and flowed through the Tri Valleys to connect with the Owens River, but no such connection has existed in the Holocene. Fish Slough is a groundwater-discharge supported marsh where groundwater from the Tri Valleys area discharges into the marsh and flows as surface water approximately 4 miles to the Owens River.

During the late-19th and early-20th century, numerous canals and ditches were excavated in Owens Valley for irrigation and drainage and many of these conveyances are still in operation today. Most are owned by LADWP and operated to supply water to lessees of LADWP-owned lands, habitat enhancement projects, and tribal lands. Canals and ditches are important sources of recharge, providing about 32,000 AFY of recharge (Hollett, 1991, Table 6). The availability of surface water for irrigation depends on snowmelt runoff, so recharge from canals and ditches varies with runoff.

Lakes are few in the OVGB, and are either artificial reservoirs or small shallow lakes occupying depressions on the Owens Valley Fault. LADWP operates Pleasant Valley Reservoir (at the north end of the OVGB), Tinemaha Reservoir (a few miles above the LAA Intake), and Haiwee Reservoir (at the south end of the OVGB), to regulate flow in the LAA (Figure 1).

<u>Groundwater System.</u> The groundwater system in the OVGB is characterized by recharge where surface water infiltrates into alluvial fans, groundwater flows down the topographic gradient toward the axis of the basin and then parallel to the axis of the valley toward the low-point of the basin at Owens Lake, where it discharges via springs, seeps, and evapotranspiration. Numerous large extraction wells operated by LADWP are present from Laws to Lone Pine. The boundaries of the basin (as presently defined), aquifer and confining units, groundwater flow, geologic structures affecting groundwater flow, the groundwater budget, and groundwater quality are presented here to complete a conceptual model of groundwater flow in the OVGB.

Basin Geometry and Boundaries. The basin boundaries are generally delineated by the contact between alluvium and the bedrock of the adjacent mountain blocks (Figure 4). At the south end of the basin, the boundary is defined by the topographic high between Owens Valley and Rose Valley. This portion of the basin boundary is in alluvium and it is uncertain whether there is a permeable pathway south to Rose Valley; however, potentiometric data suggest that Haiwee Reservoir forms a groundwater divide in this area and most studies have concluded that groundwater flow from Owens Valley to Rose Valley is small (MWH, 2011). The boundary west of Chalfant and Hammil valleys is formed by the contact between valley-fill alluvium and the

Bishop Tuff. At this boundary, the Bishop Tuff likely overlies valley fill. The northeastern boundary in Benton Valley is a jurisdictional boundary corresponding to the Nevada State line.

The bedrock boundary at the bottom of the valley fill has been characterized by geophysical methods (Pakiser et al., 1964), revealing that the basal bedrock forms deep basins separated by bedrock highs. The deepest part of the basin is beneath Owens Lake, and is about 8,000 feet deep. Another deep basin is present between Big Pine and Bishop, about 4,000 feet deep. Other basins are present east of Lone Pine and beneath Hammil Valley. Shallow bedrock is present between Chalfant Valley and Laws, between Benton and Chalfant valleys, and between Big Pine and the LAA Intake. The basis of this boundary revision request is that the bedrock high between Chalfant Valley and Laws is a barrier to groundwater flow south from Chalfant Valley to Laws, resulting in groundwater discharge at Fish Slough, and that groundwater flow from Chalfant Valley into Owens Valley is a minor part of the water budget of the two proposed subbasins.

Aquifer Units and Confining Units. Although the valley fill material of the OVGB is heterogeneous and sedimentary strata generally cannot be traced over long distances, on the valley floor, the aquifer system can be generalized into a shallow unconfined zone and a deeper confined or semi-confined zone separated by a confining unit. A review of 251 driller's logs of wells in Owens Valley found that 89% of wells had indications of low permeability material in the well log (MWH, 2003). This three-layer conceptual model was used in numerical groundwater flow models for Owens Valley (Danskin, 1998) and the Bishop-Laws area (Harrington, 2007). The shallow zone is nominally about 100 feet thick and the transmissive portion of the deeper zone goes to approximately 1,000 feet depth.

Most of the valley fill is clastic material shed from the surrounding mountains, the majority of which is sand and gravel. Alluvial fan sediments are coarse, heterogeneous, and poorly sorted at the head of the fan and finest at the toe, beyond which fans transition to lake, delta, or fluvial plain sediments (Hollett, 1991). The transition zone from fan to valley floor is characterized by relatively clean well-sorted sands and gravels that likely originated as beach, bar, or river channel deposits, and because the down-gradient valley-floor facies are finer and less permeable, the transition zone is a zone of groundwater discharge from springs and groundwater-dependent meadows (Hollett et al., 1991; Danskin, 1998). The transition zone is a favored location for LADWP groundwater wells because the well-sorted sandy aquifers provide high well yields and the transition zone corresponds to the LAA alignment. Extraction of groundwater from the transition zone has impacted groundwater dependent vegetation such that LADWP has implemented or plans to implement a number of revegetation, irrigation, and habitat enhancement projects to mitigation the effects of groundwater pumping (LADWP and Inyo County, 1991).

Although volcanic flows comprise a relatively small volume of the valley fill, the most transmissive aquifers in the Owens Valley occur in basalt flows between Big Pine and Independence. Historically, the largest springs in Owens Valley occurred where high permeability basalt flows terminate against lower permeability sediments or are in fault contact with sediments. Most of these large springs stopped flowing shortly after 1970 due to increased groundwater pumping.

Hydraulic conductivity, determined from aquifer tests in Owens Valley and the Owens Lake area, ranges from less than 10 feet/day to over 1000 feet/day (Danskin, 1998, Figure 16; MWH, 2012, Table 3-6). In Owens Valley, basalt flows between Big Pine and the Los Angeles Aqueduct Intake are highly conductive and wells intercepting such flows are the highest capacity wells in the valley. Where lacustrine sedimentation has prevailed for long periods of time at Owens Lake and Big Pine, extensive thick clay confining layers are present. Although the clay layers are disrupted and off-set by faulting, the confined nature of the deep aquifer is evident from generally higher heads in the deep aquifer than in the overlying shallow aquifer (Figure 6) and the presence of flowing wells near Bishop, Independence, and Owens Lake. A modeling effort in the Tri Valley and Fish Slough region estimated hydraulic conductivities in the range of 0.01 to 125 ft/day, with most of the values falling in the 1 to 20 ft/day range (MHA et al., 2001). These values are much lower than those from the Owens Valley and Owens Lake, possibly due to model calibration artifacts.

Groundwater Flow. Groundwater in the OVGB originates from precipitation falling within the Owens River watershed. Recharge to the aquifer system occurs primarily on alluvial fans where runoff infiltrates at the heads of alluvial fans and through stream channels. Lesser amounts of recharge derive from direct precipitation on fan surfaces; aqueduct, canal and ditch seepage; irrigation return flow; and losing reaches of the Owens River. Most natural groundwater discharge occurs on the valley floor in the form of spring flow, wetlands, baseflow to gaining reaches of the Owens River, evapotranspiration in phreatophytic vegetation communities, and evaporation from the playa and brine pool at Owens Lake. Groundwater flows from recharge areas high on the alluvial fans (areas of high hydraulic head) to discharge areas on the valley floor (areas of low hydraulic head) resulting in groundwater flow directions that parallel topographic gradients. Figure 6 shows areas of confinement, hydraulic head contours in the deep and shallow aquifers, and groundwater flow paths for spring, 1984.

Groundwater pumping has formed local cones of depression around centers of sustained pumping near Birch Creek (south of Big Pine) and Aberdeen (north of Independence), and Independence, which locally modify the regional pattern of down-fan flow on the alluvial fans and southerly flow on the valley floor.

The principal geologic structures affecting groundwater flow are the basin's bedrock boundaries and faults in the valley-fill material. The bedrock boundaries delineate the geometry of permeable valley fill. Faults parallel the axis of the valley (Figures 4 and 6) where they form barriers to groundwater flow across faults due to offset of high permeability layers and formation of low permeability material in the fault zone resulting from fault motion. Evidence for faults acting as groundwater flow barriers includes emergence of springs along fault traces and declines in water table elevation across faults. North of the Alabama Hills, blocks of aquifer are compartmentalized by en echelon faults, restricting lateral flow into the compartment. Recharge to the compartment is limited to local sources such as a stream segment within the compartment or precipitation. Absent lateral inflow, effects of pumping may be more long-lasting in compartmentalized areas, because recharge in compartmentalized aquifers may be limited to direct precipitation, which provides relatively low recharge rates.

Groundwater Budget. The groundwater budget for the OVGB is considered "understood" (Type A) according to Bulletin 118 (California Department of Water Resources, 2003). Water budgets in the OVGB have customarily separated the Tri Valley region from the Owens Valley proper. The brief discussion of the OVGB water budget in Bulletin 118 relies on data and analysis from Danskin (1998) and reports and communications from the Inyo County Water Department and LADWP. While these data sources are considered reliable, it should be noted that they pertain to the region between Laws to Lone Pine, i.e., the Tri Valley area in the north and Owens Lake in the south are not addressed in the water budget given in Bulletin 118. Water budgets for the Tri Valleys region, Owens Valley, and Owens Lake are discussed below and combined into a budget for the entire OVGB.

The Tri Valley region's water budget is the least well understood in the OVGB. A number of water budget analyses have been prepared, including Jackson (1993), MHA et al. (2001), and TEAM (2006), but each of these studies has been limited by sparse hydrologic data in the Tri Valley region. In the Tri Valley region, recharge from stream channel infiltration is not well known because only one of the fifteen streams on the west slope of the White Mountains is gauged; however, it is believed that stream channels are the predominant source of recharge, as is typical in Mojave Desert and Great Basin groundwater systems (Stonestrom et al., 2007).

Jackson (1993) estimated natural recharge by comparing the Maxey-Eakin method (Maxey and Eakin, 1949) to simply calculating 10% of the estimated average precipitation to the region, and concluded that the Maxey-Eakin's method yielded an unrealistically low value (1,270 AFY) and that the 10%-of-precipitation method provided a better estimate (13,160 AFY). MHA et al. (2001) prepared hydrologic data and a preliminary groundwater model to investigate the amount of surplus groundwater available for export. MHA's (2001) initial estimates and model-generated estimates of water budget components are given in Table 1. Inflows were initially estimated to be in the range 17,051 - 43,029 AFY and outflows estimated to be in the range 18,939 - 36,611 AFY. Using a steady-state groundwater flow model, inflow and outflow were estimated to be 27,653 AFY and 27,621 AFY respectively. Table 2 shows irrigated acreages and groundwater pumping based on 5 acre-feet/acre of applied water for the Tri Valley region and

Laws. Table 1 gives 15,485 AF of groundwater pumping for the Tri Valley region, and 5,605 AF of pumping estimated for Laws agrees reasonably well with the metered value of 6,199 AF when considering that the metered pumping includes some conveyance losses in addition to irrigation. As noted in Table 1, MHA et al.'s (2001) modeled groundwater budget allots an excessive amount of pumping to Laws by about 4,000 – 7,500 AFY (Inyo County, 2015, Table 3.1 and Figure 3.4), and underestimates spring flow discharge to Fish Slough by several thousand AFY.

Fish Slough is a groundwater discharge area outside of the OVGB, west of Chalfant Valley and north of Bishop (Figure 1). Fish Slough is a federally-designated Area of Critical Environmental Concern due to the presence of rare plants and animals. Rare phreatophytic plants and aquatic fauna at Fish Slough are entirely reliant on groundwater discharge. Although Fish Slough is outside of the OVGB, it is likely that some of the groundwater discharging from Fish Slough originates from the Tri Valley region. Jayko and Fatooh (2010) concluded that the Fish Slough fault zone captures groundwater flow from Hammil Valley and diverts it to Fish Slough.

Groundwater discharge at Fish Slough can be estimated based on water budget components. Outflow from Fish Slough is measured by LADWP at gages (Figure 7). The record for Station #1 spans water-years 1934 through 1965; the record for Station #2 spans water-years 1967 to present (Figure 8). The apparent offset between the records for Station #1 and Station #2 is unknown. Figure 9 shows a portion of the record for Fish Slough Station #2 1993 through 1996, a period during which discharge measurements for the four largest springs in Fish Slough are reliable. Discharge from the springs is seasonally constant, but discharge at Station #2 shows a regular seasonal pattern of mid-winter maxima and mid-summer minima due to the effect of evaporation from the soil surface and plant transpiration (evapotranspiration, or ET) (Pinter and Keller, 1991). To estimate groundwater discharge at Fish Slough, we assumed that the mid-winter maxima represents groundwater discharge plus direct precipitation, so subtracting the February through November monthly discharge at Station #2 from the average monthly January and December discharges gives monthly ET. Summing February through November monthly ET gives calendar-year ET, and subtracting annual precipitation falling on the high-water-table zone of Fish Slough gives ET from groundwater. The area of the high-water-table zone was evaluated from the acreage of lakes, ponds, and springs (13.9 acres), channels and welt low areas (178.2 acres) and seasonally flooded and wet alkali meadow (542.1 acres) (Odion et al., 1991) for a total of 734.2 acres. Annual precipitation was evaluated as equal to that measured at the Bishop Airport National Weather Service site (data obtained from the Western Regional Climate Center, http:wrcc.dri.edu). For the period 1967-2013, mean precipitation was 5.07 inches, and the mean ET from groundwater was 1,325 AFY. Finally adding ET from groundwater to the discharge at Station #2 gives total groundwater discharge at Fish Slough (Figure 10). For the period 1967-2013, the mean groundwater discharge was 6,397 AFY. Groundwater discharging at Fish Slough is probably a mixture of recharge from the White Mountains flowing through Hammil Valley and recharge from Casa Diablo Mountain north of the Volcanic Tablelands, in unknown proportions. Groundwater discharge at Fish Slough has steadily declined over the period 1967-2013 at a rate of approximately 100 AFY, and has declined to about one-half of its 1967 value.

When considering whether to separate the Tri Valley region and Owens Valley into two groundwater basins, a key consideration is the amount of groundwater flowing across the proposed boundary between Chalfant Valley and Owens Valley. MHA et al. (2001) estimated flow out of the Tri Valley region to be 12,524 AFY; however, Danskin's (1998) modeling study of the Owens Valley estimated that inflow into Owens Valley from Chalfant Valley was 1,665 AFY. The large discrepancy between these estimated flows may at least partially be accounted for by MHA et al.'s (2001) overstatement of pumping in Laws and understatement of groundwater discharge at Fish Slough. On this basis, and the fact that Danskin's (1998) analysis was more comprehensive than the MHA et al. (2001) study, the lower value of 1,665 AFY is probably the more reliable, but it should be noted that Danskin (1998) considered that more study was needed of this question.

The water budget for the Owens Valley is well understood because of the extensive surface water and groundwater monitoring facilities of LADWP. A water budget for the period 1970-1984 for the Owens Valley groundwater system developed by the USGS (Hollett, 1988, Table 6;

Danskin, 1998, Table 10) is shown in Table 3. The referenced USGS reports have extensive discussion of the water budget for Owens Valley and are available on the web (see reference section for URL addresses). Infiltration in stream channels of tributary streams is the largest source of recharge in the OVGB. In the Owens Valley portion of the basin north of Owens Lake, recharge from tributary streams is in the range 90,000 to 115,000 AFY (Hollett, 1991, Table 6). Danskin (1998, Plate 3) provides a map of recharge areas in Owens Valley, including stream channels, canals, ditches, agricultural return flows, ponds, and areas where precipitation infiltrates directly to the groundwater system. Subsequent work in Owens Valley conducted in support of the Inyo County/City of Los Angeles Water Agreement (see SGMA section 10720.8 (c)) using the same methods as Danskin (1998) shows that recharge over the period from water-year 1990 through 2014 averaged 162,000 AFY with a maximum of 251,000 AFY in 2006 and a minimum of 109,000 in 2014 (LADWP, 2015). Over this same period, groundwater pumping by LADWP has averaged 78,000 AFY, ranging from 57,000 AFY in 2006 to 93,000 AFY in 1990 (data on file at Inyo County Water Department). Non-LADWP pumping in Owens Valley is relatively small, and includes pumping for the City of Bishop, a number of small public water suppliers, domestic wells scattered up and down the valley, and a few agricultural pumpers on private land. Non-LADWP pumping is less than 10,000 AFY.

The water budget for the Owens Lake portion of the OVGB is well understood from monitoring conducted by the LADWP and the Great Basin Air Pollution Control District. The most comprehensive water budget for the Owen Lake groundwater system was recently completed by consultants for LADWP (MWH, 2011). MWH (2011, Table 16) estimate recharge to range from 44,000 to 67,500 AFY (Table 4) and reconciled this estimate with evapotranspiration and groundwater exports from the Owens Lake area to arrive at a recharge estimate of 51,700 AFY. MWH (2011) estimated evapotranspiration of groundwater in the Owens Lake area to be 66,400 AFY, but attributed 15,000 AFY of this figure to surface water entering the area via the Lower Owens River. MWH (2011) accounted for 300 AFY of pumping for a water bottling plant at Cartago. In Table 4, 2,000 AFY has been added to account for irrigation pumping in the Olancha area.

Water budget information from the Tri Valley region, Owens Valley, and the Owens Lake area can be combined to develop a basin-wide water budget for the OVGB. Table 5 reconciles the water budgets for each of the subbasins in the OVGB. Discharge from the Tri Valley region included an additional 4,357 AFY of spring discharge to account for recent (2013) levels groundwater discharge at Fish Slough (Figure 10). Figures given for Owens Valley represent average conditions. Recharge for the Owens Lake region was decreased to not count groundwater flow from the north, and discharge at Owens Lake was decreased to account for 15,000 AFY of surface water from the Lower Owens River. Additionally, the Owens Valley study area (Danskin, 1998) and the Owens Lake study area (2011) overlap in the area of Lone Pine, Tuttle, Diaz, and Lubkin Creeks. Based on Danskin's (1998) recharge calculations, 10,600 AFY was subtracted from the basin-wide recharge figures so as to not "double count" recharge in this area (see City of Los Angeles Department of Water and Power and Inyo County, 1990), Appendix B Tables 2, 3, and 4). The overall water budget given in Table 5 represents average conditions, and interannual variations are likely in the range of plus or minus 50% from the average values. Table 5 shows an overall balance between recharge and discharge, with extracted groundwater accounting for 43 – 54 % of recharge on average. Groundwater flow from the Tri Valley region to Owens Valley is less than 1% of the overall basin water budget.

Groundwater Quality. Groundwater quality in the OVGB is generally good. Total dissolved solids in the Tri Valley region at a small public water system in Chalfant Valley ranged from 240 to 298 mg/L (TEAM, 2006). In Owens Valley, total dissolved solids generally ranged from 108 to 325 mg/L in a selection of wells and generally of a calcium-bicarbonate composition (Hollett, 1991, Table 5); however, at Owens Lake total dissolved solids range from fresh (222 mg/L) to saline (20,983 mg/L) mainly dependent on the source aquifer (MWH, 2012). Human-caused groundwater contamination consists of leaky underground storage tanks and land disposal facilities (California State Water Resources Control Board). Naturally occurring arsenic is present in groundwater at Owens Lake.

Summary

The Owens Valley Groundwater Basin is an elongate depression formed by Basin and Range-style extensional faulting. Valley fill consists of a heterogeneous mix of alluvium, fluviolacustrine (stream and lake), and volcanic material. Although the basin presents a continuous surface of valley fill of about 120 miles, geophysical studies have shown that the basin consists of a series of deep basins separated by relatively shallow bedrock blocks. Because the basin consists of a series of deep basins with intervening bedrock blocks, the basin can be divided into three discrete hydrologic units – Tri Valley, Owens Valley, and Owens Lake – and groundwater studies have customarily treated these areas as separate water budget units.

The aquifer system is conceptualized as having a shallow unconfined zone and a deep confined or semi-confined zone, separated by a confining layer or layers. Confinement is more pronounced in the center of the valley where clayey layers are more laterally continuous. On alluvial fans, the system generally consists of a single unconfined system as confining layers pinch out toward the margins of the basin. Recharge occurs primarily at the heads of alluvial fans and along stream channels on alluvial fans. Groundwater generally flows down the topographic gradient of the fans toward the axis of the valley, and then parallel to the axis toward Owens Lake, the low point of the Owens Valley. Natural groundwater discharge occurs in springs, seeps, wetlands, groundwater-dependent vegetation communities, and as baseflow to the Owens River. Groundwater has been developed for domestic, municipal, agricultural uses and to supply water to Los Angeles via the Los Angeles Aqueduct. The principal pumper in the basin is the Los Angeles Department of Water and Power, which pumps water both for export and for use on Los Angeles-owned lands in Owens Valley. Total groundwater extraction from pumped and flowing wells is approximately 43-54% of recharge on average.

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Tables

Table 1. Water budget components (AFY) for Tri Valley region from MHA et al. (2001), Tables 5-8 and 6-6.

Initial Estimates of Water Budget Components

Inflow	Low Estimate	High Estimate	Comments
White Mountain runoff	14,100	25,829	Extrapolated from gauged streams
Precipitation	0	0	Likely greater than zero, but small
Benton Range	1,500	1,500	Unknown
Bishop Tuff	1,000	1,000	Unknown
Return flows	451	14,700	Lower estimate is more recent
Total Inflows	**17,051**	**43,029**	
Outflows			
Ag and domestic pumping	16,200	19,629	Estimates are close and consistent
Phreatophytic ET	1,084	3,282	Preliminary vegetation mapping, which includes Fish Slough, yields 1,084 AFY
Subsurface outflow	1,655	13,700	Lower estimate from Danskin (1998), higher from PWA (1980)
Total Outflows	**18,939**	**36,611**	

Calibrated Steady-State Model

Inflows	Calibrated value	Comments
Boundary inflows	35	
Recharge	27,463	
Owens River	155	Model domain extended to Owens River.
Total Inflow	**27,653**	
Outflows		
ET	593	Principally at Fish Slough and Chalfant
Pumping	26,898	Includes 14,481 AFY from Laws, which is 4,000 – 7,000 AFY too high for steady-state conditions
Fish Slough	5	Fish Slough groundwater discharge to surface water is 3,000 – 6,000 AFY
Owens River	165	
Boundary outflow	0	Model estimate of flow from Chalfant to Laws was 14,481 AFY
Total Outflow	**27,621**	

Table 2. Irrigated acreage determined from 2014 aerial photography and groundwater pumping for irrigation assuming 5 acre-feet/acre of applied water.

Area	Irrigated acres	Groundwater pumping
Benton Valley	514	2,570
Hammil Valley	2,383	11,915
Chalfant Valley	200	1,000
Laws	1,121	5,605
Total	4,218	21,090

Table 3. Groundwater budget components for Owens Valley (not including Round Valley and Owens Lake) for water-years 1970-1984 (Danskin, 1998, Table 10).

Component	Average	Minimum	Maximum
Precipitation	2,000	0	5,000
Evapotranspiration	-72,000	-50,000	-90,000
Tributary streams	103,000	90,000	115,000
Mountain front recharge	26,000	15,000	35,000
Runoff from bedrock outcrops in valley fill	1,000	0	2,000
Owens River above intake and LA Aqueduct			
Channel seepage	-3,000	0	-20,000
Spillgates	6,000	3,000	10,000
Owens River below LA Aqueduct intake	-3,000	-1,000	-8,000
Reservoirs and lakes	1,000	-5,000	5,000
Canals, ditches, ponds	31,000	15,000	60,000
Irrigation returns and stock water	10,000	5,000	20,000
Pumped and flowing wells	-98,000	-90,000	-110,000
Springs and seeps	-6,000	-4,000	-10,000
Subsurface inflow	4,000	3,000	10,000
Subsurface outflow	-10,000	-5,000	-20,000
Total recharge	**184,000**	**170,000**	**210,000**
Total discharge	**192,000**	**175,000**	**225,000**
Change in groundwater storage	**-8,000**	**-5,000**	**-15,000**

Table 4. Recharge estimates for the Owens Lake area (from MWH (2011), Table 16).

Component	Recharge (AFY)
Down-valley flow from north	12,500 – 14,500
Recharge from stream channels	
Inyo/Coso ranges	0 - 2,000
Sierra Nevada (Lone Pine to Lubkin Creek)	15,750
Sierra Nevada (Carroll to Walker Creek)	8,000 - 18,500
Interfluve/alluvial fan recharge	0 - 2,000
Haiwee Reservoir subsurface inflow	2,000 - 10,000
Centennial Flat subsurface inflow	0 - 1,000
Mountain block recharge	0
Total	**44,000 - 67,500**

Table 5. Owens Valley Groundwater Basin water budget, based on water budgets for the Tri Valley region, Owens Valley, and Owens Lake area (Tables 1-4).

	Recharge	Discharge	
		Pumping	ET, springs and seeps, baseflow to water courses
Tri Valley region	17,000 - 43,000	16,200 - 19,600	5,000[1]
Owens Valley	183,800	98,000[2]	84,000
Owens Lake	29,500 - 55,000	2300[3]	51,400
Subtotal	230,800 - 281,900	116,500 – 119,900	141,400
Total	**220,200 - 271,300[4]**	**251,900 - 260,300**	

[1] 4,400 AFY groundwater discharge at Fish Slough plus 600 AFY discharge in Chalfant Valley.
[2] 78,000 AFY pumping by LADWP plus 10,000 AFY by non-LADWP pumpers, plus 10,000 AFY from flowing wells.
[3] Includes 2,000 AFY for irrigation and 300 AFY for water bottling plant.
[4] 10,600 AFY was subtracted to account for overlap Owens Valley (Danskin, 1998) and Owens Lake (MWH, 2011) study areas.

Figures

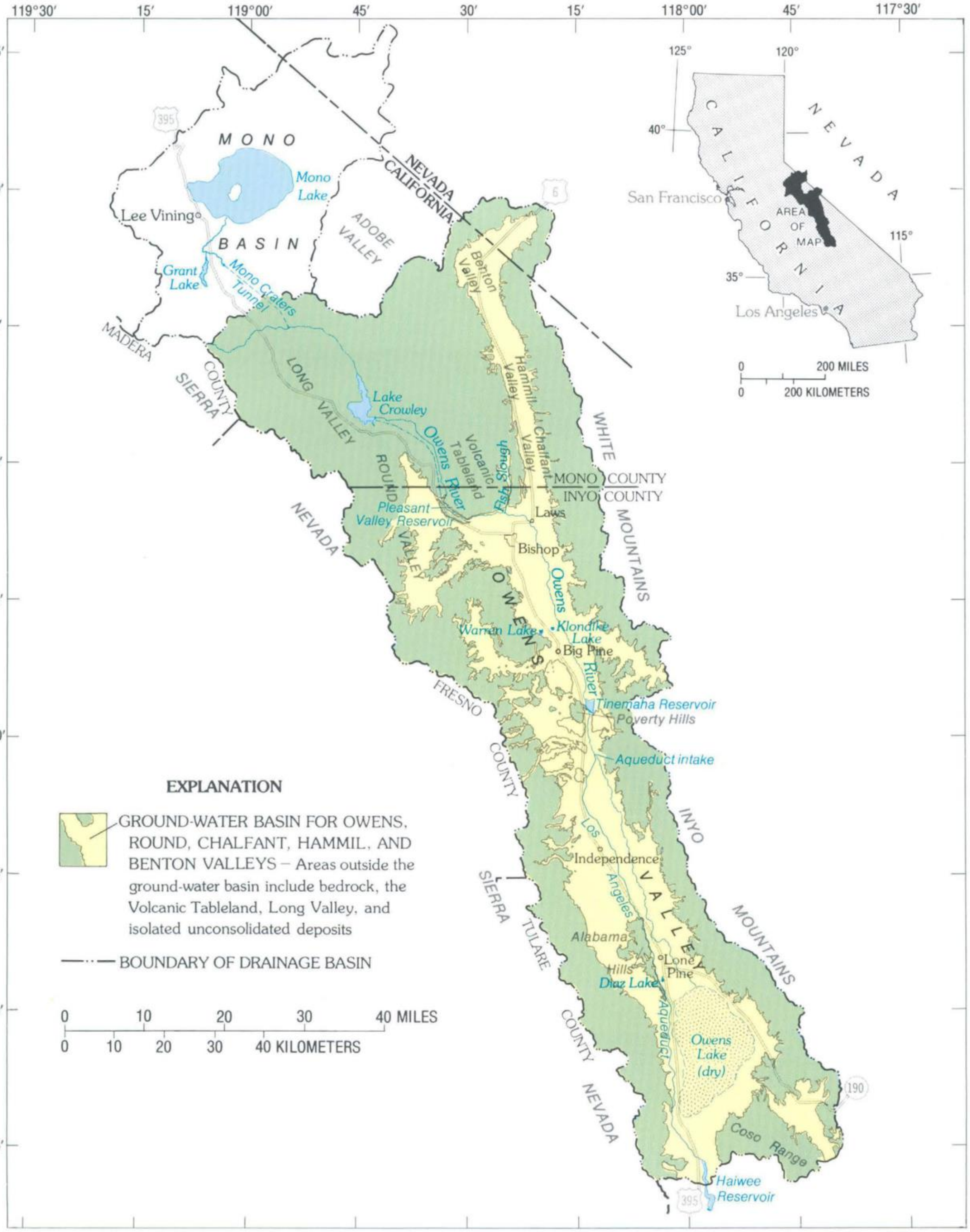


Figure 1. Owens River watershed and Owens Valley Groundwater Basin (from Hollet et al., 1991, courtesy of US Geological Survey).

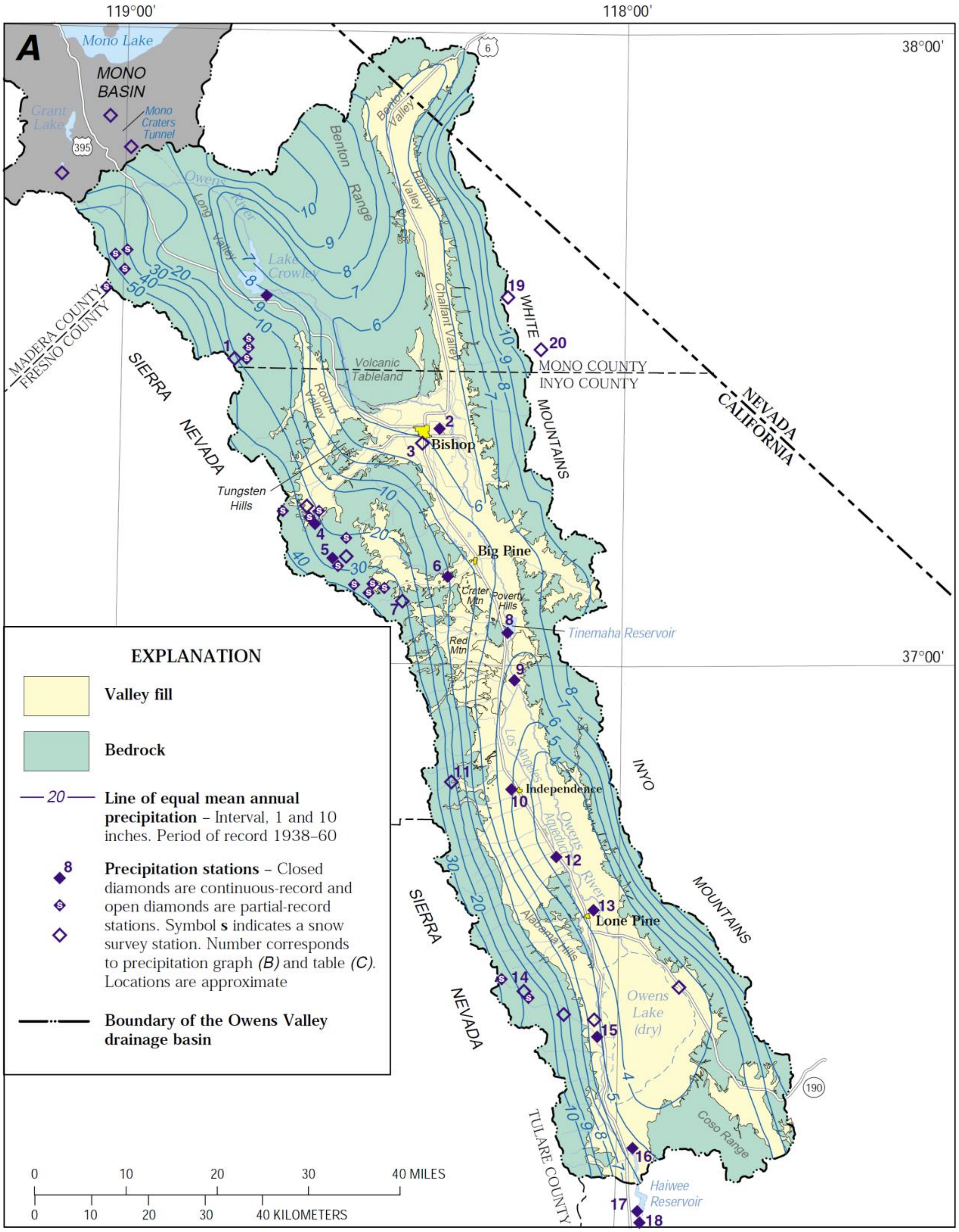


Figure 2. Isohyetal (precipitation) contours for Owens River watershed (from Hollet et al., 1991, courtesy of US Geological Survey).

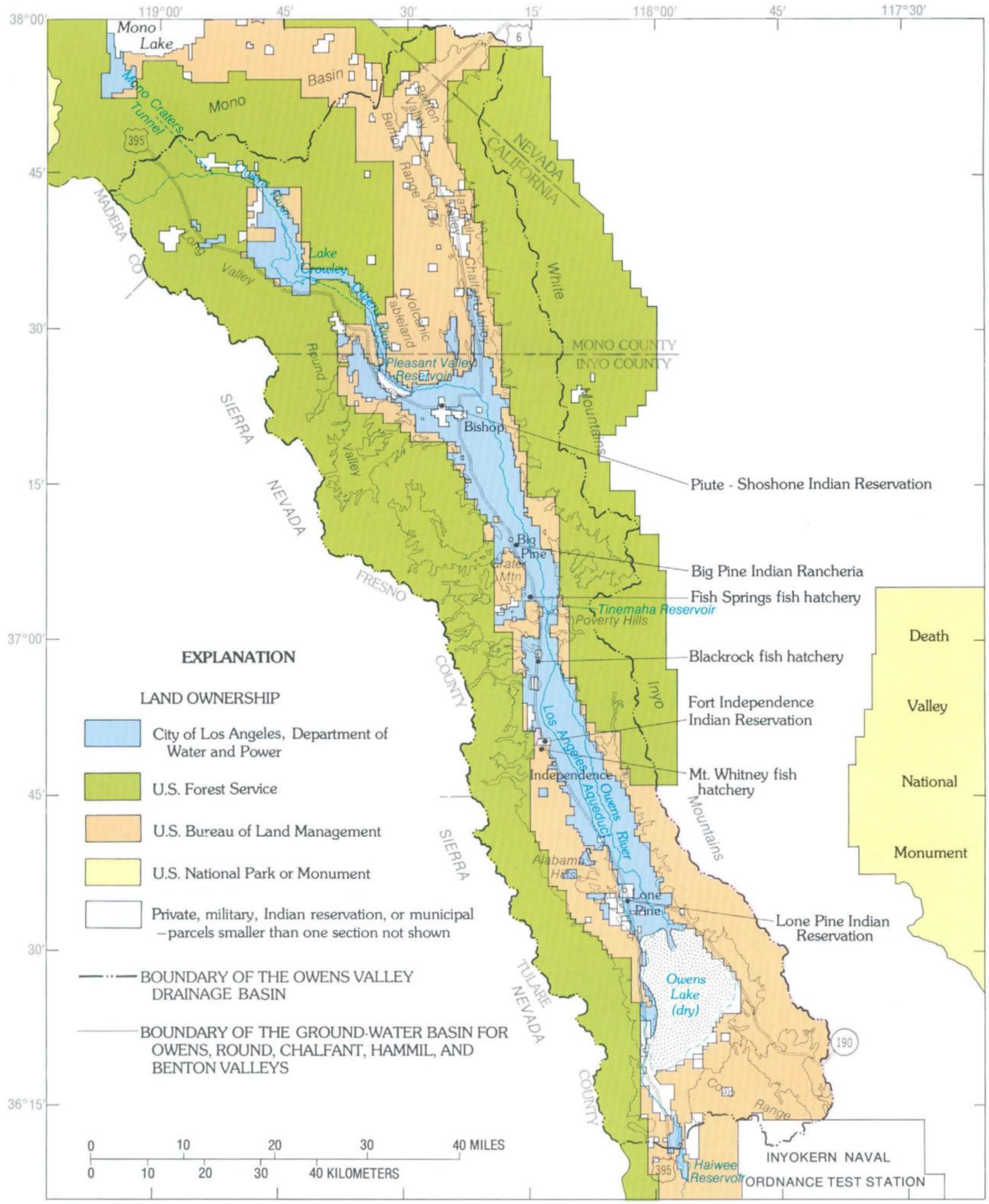


Figure 3. Land ownership in Owens watershed. Note that the Owens Lake bed is largely owned by the California State Lands Commission (Hollett et al., 1991, courtesy of US Geological Survey).

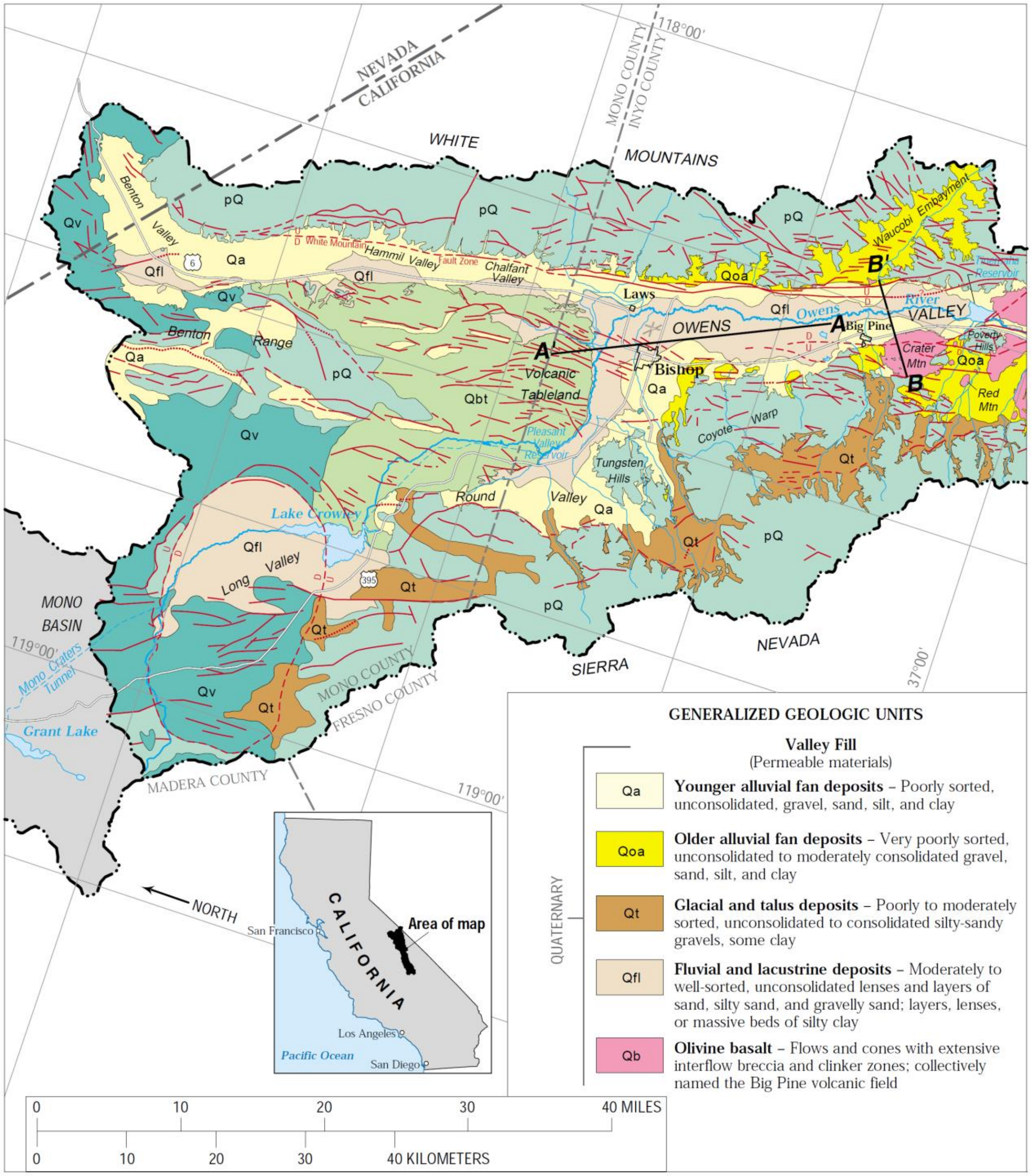


Figure 4. Geology of the Owen Valley Groundwater Basin and vicinity (Danskin, 1998, courtesy of US Geological Survey).

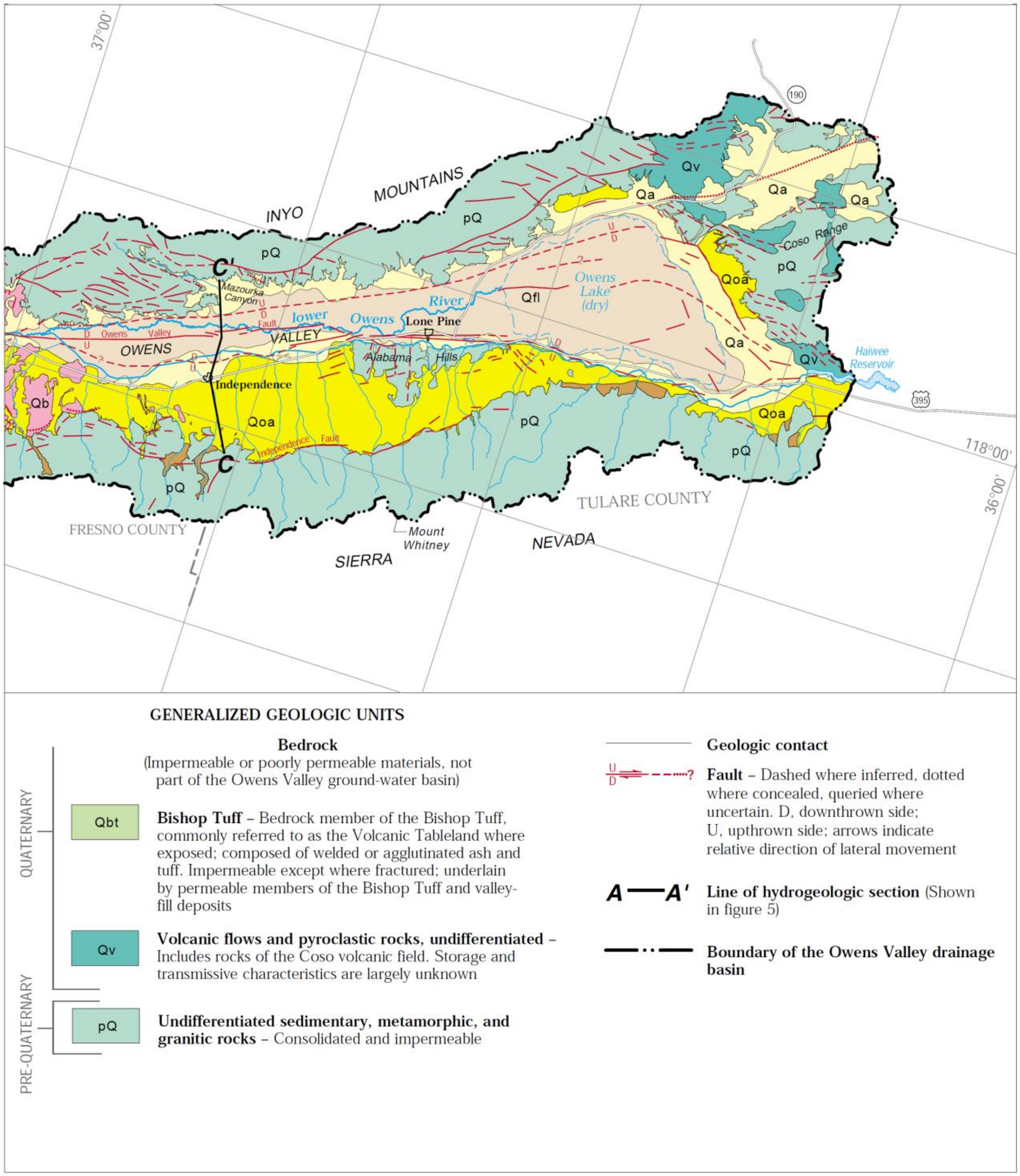


Figure 4. Continued from previous page.

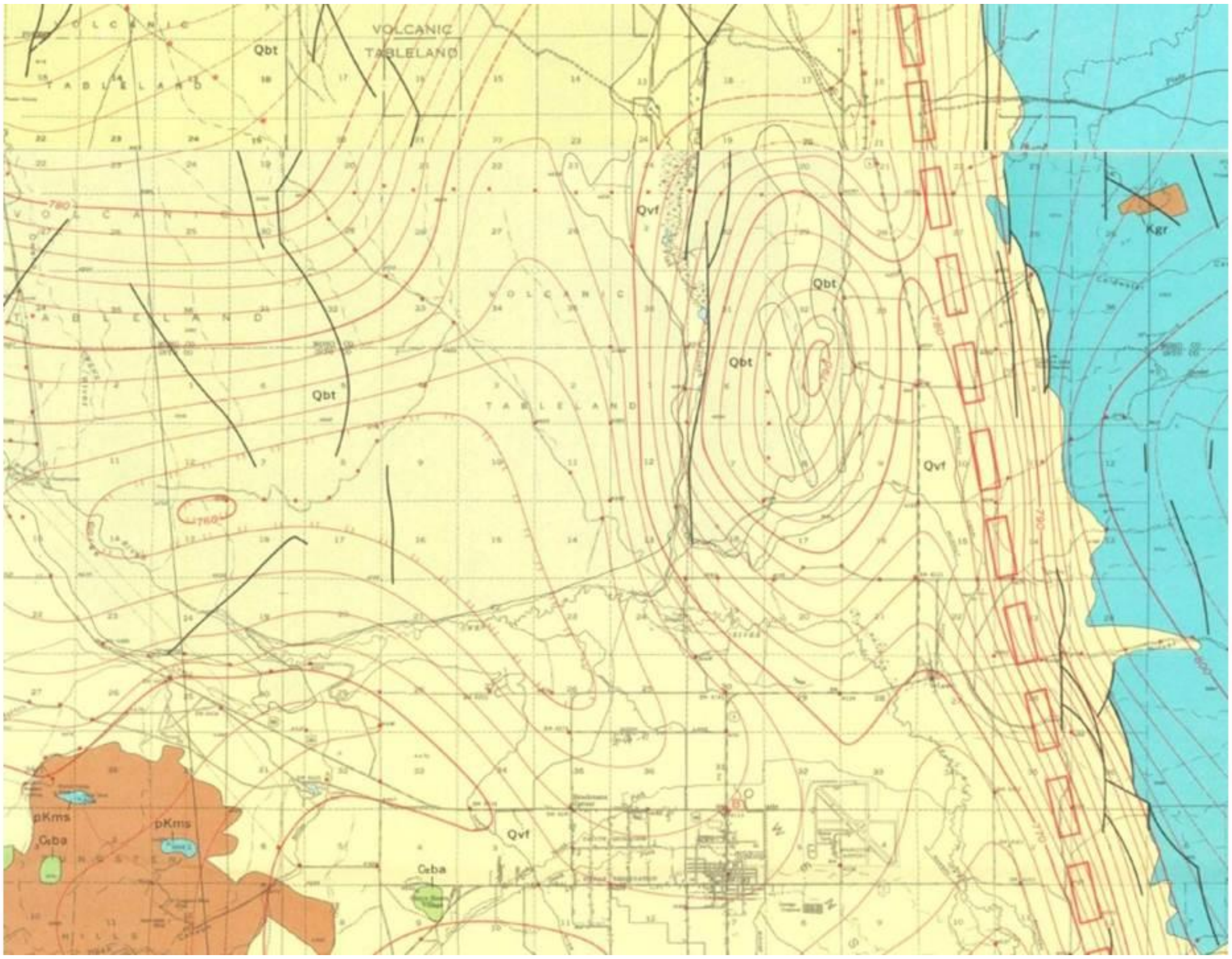


Figure 5a. Gravity contour and structural geology of Bishop/Chalfant Valley region, showing gravity anomaly between Owens Valley and Chalfant Valley. Bishop is located in lower center; Fish Slough is the wetland indicated in the upper center, with the Fish Slough Fault running along its eastern boundary; the gravity anomaly is indicated by the closed gravity contours east of Fish Slough. This map is a composite of portions of Plate 1, Sheets 1 &2 from Pakiser et al. (1964). Key is provided in Figure 5b.

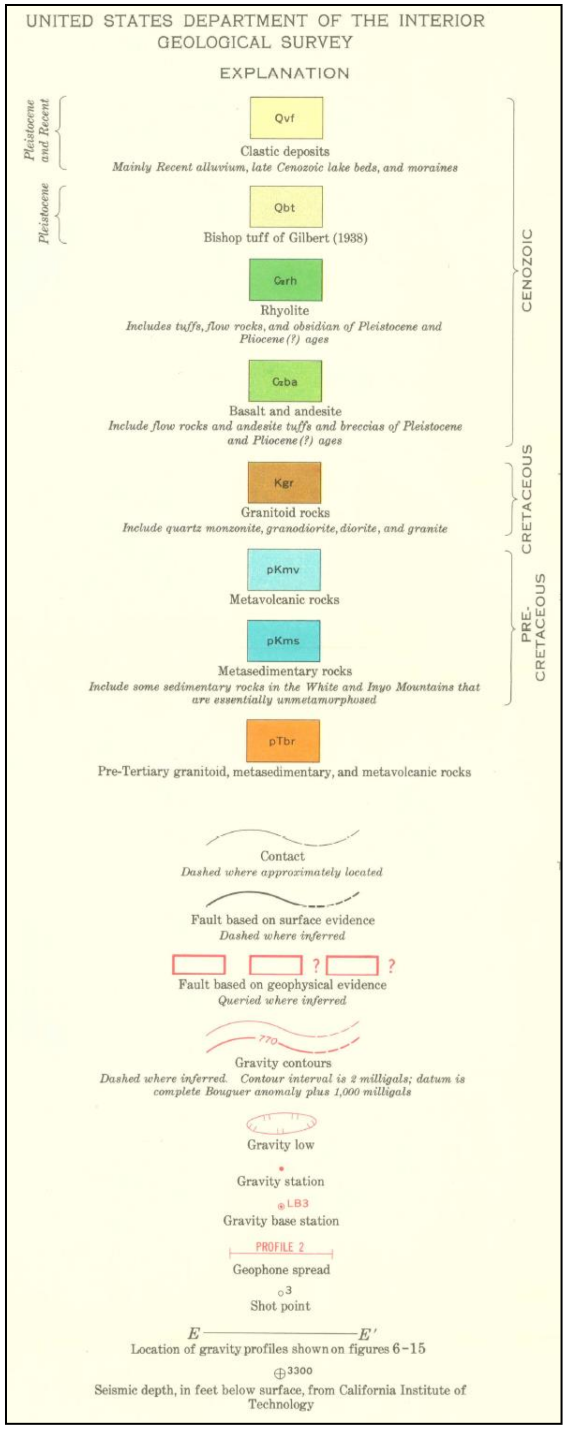


Figure 5b. Key to Figure 5a.

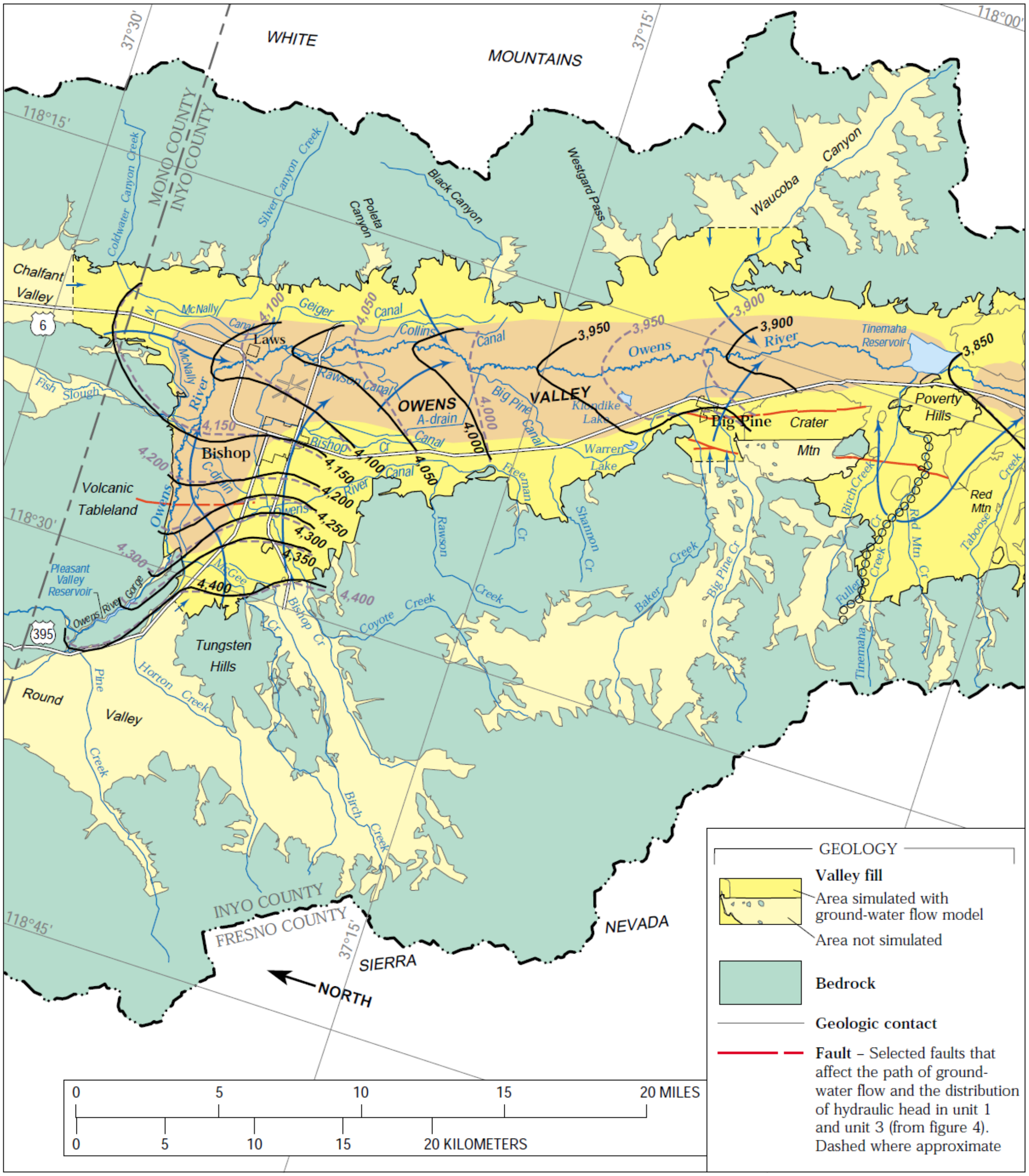
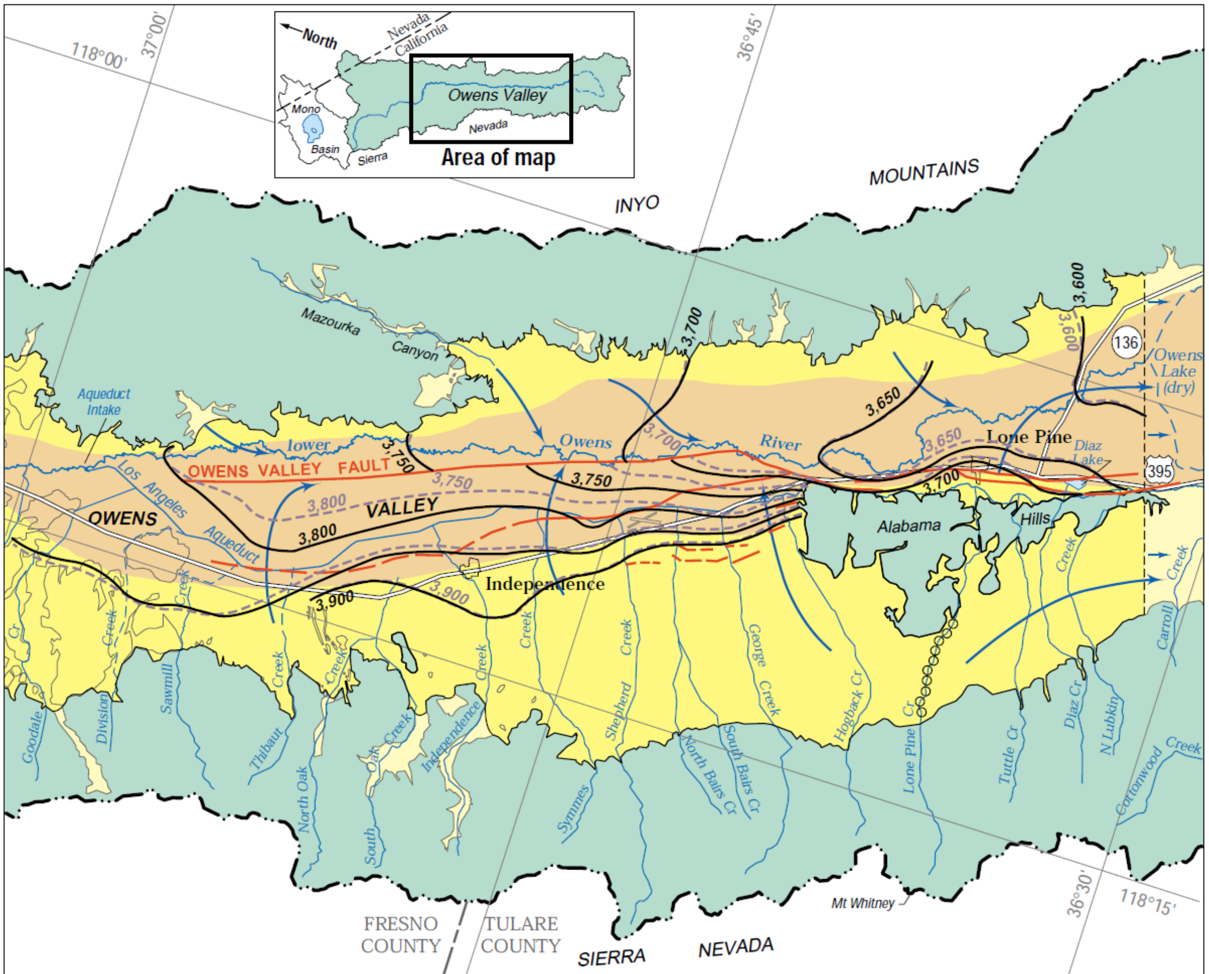


Figure 6. Groundwater flow conditions between Bishop and Lone Pine. Shown are areal extent of aquifer, zone of confined aquifer, hydraulic head contours in deep and shallow aquifer, and groundwater flow directions (from Danskin, 1998, courtesy of U.S. Geological Survey).



EXPLANATION

HYDROLOGY

Approximate extent of the confined part of the aquifer

Potentiometric contour – Shows approximate altitude of the water table in hydrogeologic unit 1, represented by the upper layer of the ground-water flow model, spring 1984. Contour interval 50 feet. Datum is sea level (3,900)

Potentiometric contour – Shows approximate altitude of the hydraulic head in hydrogeologic unit 3, represented by the lower layer of the ground-water flow model, spring 1984. Contour interval 50 feet. Datum is sea level (3,900)

Generalized direction of ground-water flow – Combined direction of ground-water flow in hydrogeologic units 1 and 3

Ground-water divide – Approximately located

Boundary of the aquifer system – As defined in this report. Arrows indicate the direction of ground-water flow to or from adjacent permeable materials

Boundary of the Owens Valley drainage basin

Figure 6 (continued).

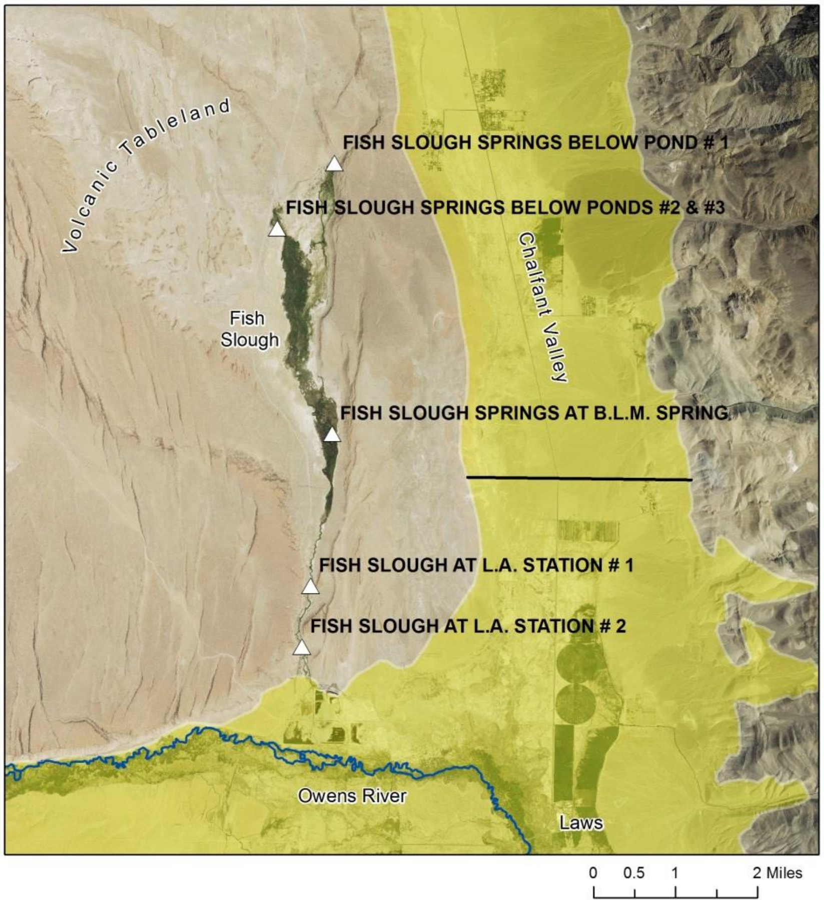


Figure 7. Locations of surface water flow gages used to estimate groundwater discharge at Fish Slough. Location of proposed boundary revision is shown by black line.

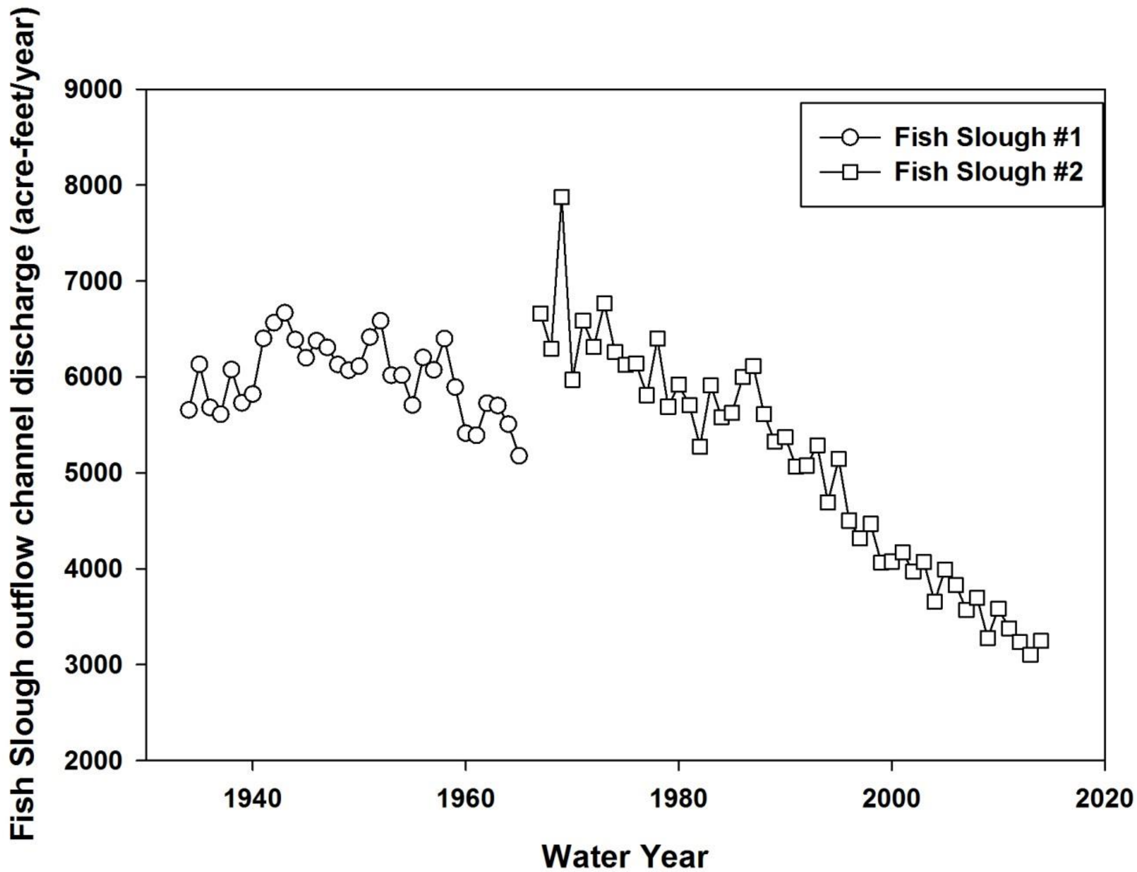


Figure 8. Surface water outflow from Fish Slough. Fish Slough Station #2 is on Fish Slough Ditch at the Upper McNally Canal; Fish Slough Station #1 was located on Fish Slough Ditch approximately 1 mile upstream of Station #1. The cause of the offset between the last measurements from Station #1 and the first measurements from Station #2 is unknown.

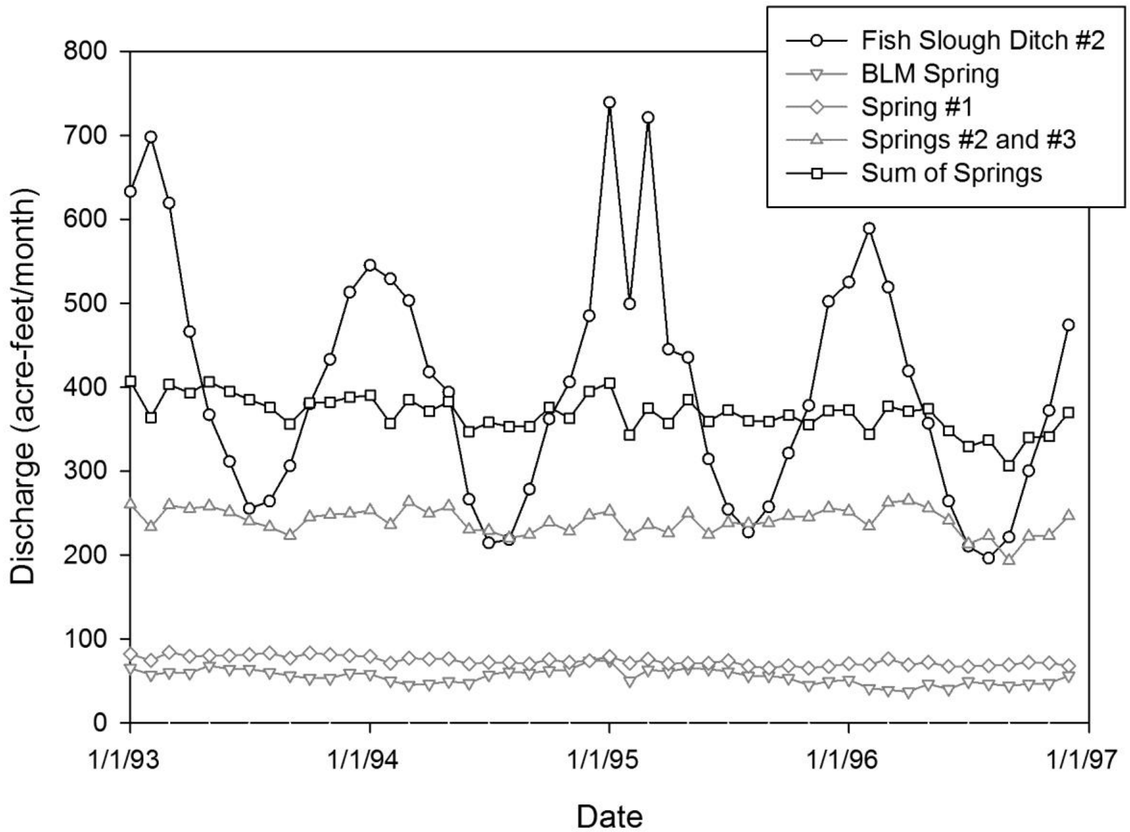


Figure 9. Outflow from Fish Slough at LADWP Fish Slough Ditch Station #2 and discharge from gaged springs in Fish Slough. Sum of springs is the sum of the three gaged springs.

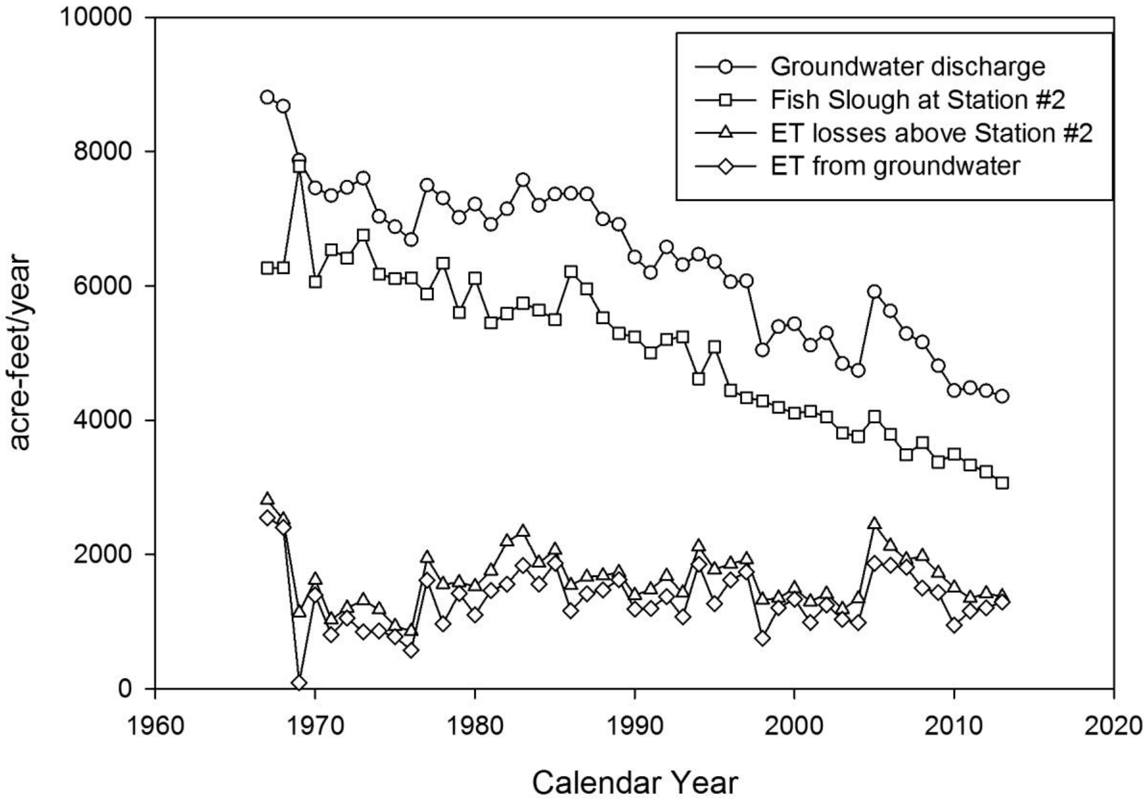


Figure 10. Groundwater discharge at Fish Slough estimated by attributing season fluctuations in flow at Fish Slough Station #2 to evapotranspiration (ET) and accounting for precipitation.