DEVELOPMENT OF A GROUNDWATER FLOW MODEL FOR THE BISHOP/LAWS AREA

FINAL REPORT FOR LOCAL GROUNDWATER ASSISTANCE GRANT AGREEMENT

NO. 4600004129

Robert Harrington, PhD, R.G.

INYO COUNTY WATER DEPARTMENT

APRIL, 2007

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EXECUTIVE SUMMARY

A steady-state numerical groundwater model for the Bishop-Laws area was developed based on a conceptual model incorporating the study area's geologic materials, tectonic setting, and surface water hydrology. The steady-state model was used to generate initial conditions for two transient applications of the model. The first transient application of the model determined the amount of drawdown that would be caused by full operation of new production wells that have been proposed for construction. The second transient scenario looked at how water levels change when canal operations are reduced in Laws. These two applications are relevant to recent groundwater issues that Los Angeles Department of Water and Power and Inyo County have joint responsibility for managing.

The steady-state model was calibrated to recent hydrologic conditions. Both manual and automated calibration were used to achieve an overall calibration where the residual standard deviation was 2.9% of the range in target heads. Additionally, discharge from flowing wells and water balance components were used in the calibration process to ensure that the model was a reproducing the hydrology of the study area.

LADWP plans to install seven new wells in the Bishop-Laws area. Modeling of full operation of these wells indicated that they would develop an extensive cone of depression up to about 5.0 m near wells. A court decree limits LADWP pumping and flowing well discharge in the Bishop area to not greater than the amount of water used on LADWP lands in the area. In the past, this court decree has been considered adequate to limit pumping near Bishop, and none of the management constraints applied elsewhere in the Owens Valley have been implemented in Bishop. Because the proposed new wells could result drawdowns that could cause impacts to native vegetation, additional management of groundwater pumping in the Bishop area may be necessary in the future.

The model was used to determine the effect of the McNally Canals on the water table in Laws. Operation of these canals has been a point of dispute between LADWP and Inyo County, which centered on whether diminished use of the canals to move water into

Laws was reducing the amount of water available for native phreatophytic vegetation. Reducing recharge from the McNally Canals resulted in the reductions in water table elevation of up to 4 meters beneath parcels of groundwater dependent vegetation.

The model developed for this study was designed flexibly so that it can be applied to water management issues in the future. While the applications described above are relevant to current groundwater management problems, their purpose here was primarily as heuristic explorations of the utility and flexibility of the model. The Groundwater Vistas graphical user interface allowed the transient applications to be efficiently developed from the steady-state model, and model output to be easily extracted and interpreted. Because the model was developed within the Inyo County Water Department, future applications can be developed in-house.

INTRODUCTION

Modeling Objectives. The objective of this study was to develop a model of the Bishop-Laws area to evaluate the effect of water management activities on groundwater dependent resources and existing groundwater users. A large portion of the land in the project area is owned by the City of Los Angeles and managed by the Los Angeles Department of Water and Power (LADWP). Private, tribal, and Bureau of Land Management lands also lie within the project area. In 1991, the County of Inyo and the City of Los Angeles and LADWP adopted a "Long Term Groundwater Management Plan for the Owens Valley and Inyo County" (Plan) as part of a settlement of two decades of litigation over the effects of Los Angeles' pumping and export of groundwater from the Owens Valley. A primary goal of the Plan is to protect native vegetation from impacts from groundwater pumping. Under the Plan, Inyo County and LADWP jointly manage water resources in the project area. This model will assist Inyo County in meeting its joint management obligations under the Plan.

The uses of this model are to develop and assess alternative groundwater management strategies, and evaluate the effect of proposed projects, changes in groundwater usage, or other stresses on the groundwater system. Because the City of Los Angeles' land holdings are so extensive, the LADWP's water management activities are the primary application of this model; however, potential applications of the model are not limited to LADWP-related issues. Current applications of the model include evaluations of proposed new wells, evaluation of changes in operations of existing wells, and evaluation of changes in canal operations.

Model Function. To fulfill the goals of the study, a steady-state groundwater model was developed based on recent conditions, and two transient drawdown predictions were developed based on the steady-state model. The steady-state model was calibrated to extant heads and discharges, and the drawdown predictions generated by superposing perturbations on the steady-state model. The first predictive scenario was based on construction and operation of new wells described in the Plan. The second predictive scenario was based on alteration of recharge from canals in the Laws area. The operation of canals has been a subject of a recent dispute between LADWP and Inyo (James, 2001).

Land use. The project area is within the Owens Valley, an elongate north-south valley located in eastern central California, which is a primary source of water for the City of Los Angeles. Shallow groundwater in the floor of the valley supports groundwater-dependent meadows, springs, scrublands, and baseflow to the Owens River. Native vegetation in the study area includes riparian areas along the Owens River, along stream courses in mountain canyons and alluvial fan surfaces, and along ditches and canals diverting water from natural water courses, marshes and wetlands in the Fish Slough area and along the valley bottom, groundwater dependent meadows and scrub in the valley bottom, and xeric scrub on alluvial fan surfaces. The study area contains approximately 22,000 ha (9,000 acres) of irrigated agriculture and pasture. Inyo County's highest concentration of population and urbanized development is within the project area, comprising approximately 10,000 people, primarily within the Bishop and west Bishop areas.

Physiography and Climate. The Bishop-Laws area is at the north end of the Owens Valley, flanked on the east by the White Mountains and on the west by the Sierra Nevada (Figure 1). Altitudes within the model domain range from about 1,220 m amsl (4,000 ft) on the valley floor to over 1,540 m amsl (5,000 ft) on the Bishop Creek alluvial fan. The mountains adjacent to the study area rise to over 3,900 m amsl (13,000 ft) in the Sierra Nevada and 4,200 m amsl (14,000 ft) in the White Mountains. The study area is characterized by the flat valley bottom of the Owens River, river terraces, alluvial fans flanking the ranges, and the gently sloping surface of the Volcanic Tableland. The valley is filled with several thousand feet of alluvial fan, river, volcanic, and lake deposits, the more permeable of which are exploited for groundwater production for local use and for export to the City of Los Angeles via the Los Angeles Aqueduct. These aquifers are recharged primarily by streambed infiltration of snowmelt runoff from the mountains, seepage from ditches and canals, and infiltrations from irrigation, with only minor contributions from precipitation on the valley floor.

The floor of the Owens Valley is semi-arid, receiving an average of 15 cm/yr (6 inches/yr) of precipitation, primarily from moist winter and spring frontal storms moving inland from the Pacific Ocean. These storms encounter the Sierra Nevada before they reach the study area, and the orographic effect of the Sierra Nevada creates a rain shadow, depriving the study area and other regions east of the Sierra of precipitation. Average annual precipitation is as high as 130 cm/yr (50 inches/yr) in the Sierran Nevada and 25 cm/yr (10 inches) in the White Mountains (Danskin, 1998). Runoff in the study area is dominated by springtime melt of the seasonal mountain snowpack, resulting in peak runoff in late-spring and early-summer, and runoff minima in the late-fall and winter. Annual runoff for the Owens Valley ranges from about 50% to 200% of its mean value. Though the majority of precipitation occurs in the winter, sporadic localized summer thunderstorms can also generate high precipitation rates for short periods of time. Air temperatures from the National Weather Service station at Bishop Airport range from –9F to 107F, often with wide diurnal changes in temperature due to the dry climate and clear skies. Reference evapotranspiration at the California Irrigation Management System station in Bishop is about 150 cm/yr (60 inches/year) (CIMIS, 2003).

The main surface water features of the study area are the Owens River, its tributaries from the Sierra Nevada, and the network of diversion ditches and canals that route water from the river and creeks through both Bishop and Laws. Flows in the Owens River through the study area are controlled by Pleasant Valley Dam, located at the western edge of the study area. Annual average releases from Pleasant Valley Reservoir range from 317,000 m^3/day (129 cfs) to 1,160,000 m^3/day (474 cfs), averaging 655,000 m^3/day (267 cfs). Flows in Bishop Creek, the largest tributary in the study area, range from 47,000 m^3/day (19 cfs) to 454,000 m^3/day (185 cfs), averaging 233,000 m^3/day (95 cfs).

CONCEPTUAL MODEL

Geologic Framework. The Owens Valley lies at the western edge of the Basin and Range tectonic province, a region characterized by fault block ranges and valleys produced by regional east-west tectonic extension. Typical of the Basin and Range, the Owens Valley is an elongate north-northwest trending alluvium-filled fault-bounded graben. Bounding the valley on the west is the Sierra Nevada, consisting primarily of Mesozoic granitic batholith rocks with remants of the pre-batholithic marine sediments present as septa between plutons (Bateman, 1965). South and west of Bishop, the Sierra range front fault gives way to a broad northeast plunging anticlinal warp known as the Coyote Warp. North of the Coyote Warp, the range front fault resumes along the base of the Wheeler Crest. In the vicinity of the study area, the White Mountains consist primarily of highly deformed Paleozoic marine sediments. The western escarpment of the White Mountains is bounded by a relatively narrow fault zone along the eastern margin of the study area.

The basin fill provides the most important water bearing rocks of the study area. The clastic and volcanic deposits filling the valley are of higher permeability than the plutonic and metamorphic rocks of the mountain blocks. Therefore, the groundwater model considers flow to occur only in the valley fill deposits. The valley fill consists of primarily detritus from the Sierra Nevada and White Mountains, Bishop Tuff, and minor basaltic necks and flows. The detrital rocks are present as poorly sorted fan material, moderately-sorted to well-sorted fluvial gravels and sands, and lacustrine clays. Moraines are present at the head of the Bishop Creek fan, however these deposits play little role in the overall hydrogeology of the study area.

The fan deposits consist of debris flows and fluvial material issuing from the mountain canyons. The Sierran fans are large and coalesce into a continuous bajada along the range front, whereas the White Mountains' fans are smaller and consist of individual fans at the mouths of canyons. The contrast in fan size and coalescence between the White Mountains and Sierra Nevada is due to higher erosion rates in the Sierra Nevada; higher precipitation and glaciation in the Sierra Nevada has resulted in larger volumes of sediment deposited on the fans.

The Bishop Tuff was erupted from the Long Valley caldera 0.76 Ma and deposited as tephra and pyroclastic flows, which resulted in the rhyolitic tuff present in the study area today. Northwest of the study area, in the Owens River Gorge, the thickness of exposed Bishop Tuff exceeds 150 m (500 ft), but exposures in the study area do not exceed 45 m (150 ft), typically occurring as a basal unwelded ash and pumice layer overlain by a weakly to moderately welded ignimbrite. Isolated pockets of tephra occur on the flanks of the White Mountains on the eastern margin of the study area. The Volcanic Tablelands, in the northwest part of the study area, is a southeastly sloping surface of exposed Bishop Tuff, terminating on the south by the Owens River and on the east by the Laws area and Chalfant Valley. The Volcanic Tablelands surface is offset by many north-striking normal faults, with apparent offset typically of 3 to 10 m (10 to 30 ft). Dinwiddie et al. (2006) have shown that faulting of unwelded Bishop Tuff increases matrix permeability in fault damage zones, but note that fine grained gouge on fault surfaces reduces permeability. The Bishop Tuff is intercalated with alluvial valley fill beneath the study area and often overlain by gravel, providing a marker bed in boreholes drilled in the valley fill (Bateman, 1965). Inferred from borehole data, the Bishop Tuff thins and deepens to the south and is down-warped and possibly faulted down to the west in the center of the study area.

The hydrogeologic behavior of the Bishop Tuff is uncertain. Driller's logs for boreholes in the Bishop-Laws area often report flowing groundwater when the Bishop Tuff was encountered, and Bateman (1965) states that "the tuff underlying the valley is almost certainly unconsolidated," however, some driller's logs refer to "hard tufa", "broken tufa", "tufa rock", "solid pink tufa", and "solid white tufa", suggesting that at least some of the tuff underlying the valley is agglutinated. Other driller's notes such as "tufa sand water", "fine sand, pumice, and tufa", and "tufa loose water" suggest unconsolidated tuff acting as a high-transmissivity zone. It is uncertain whether the flowing groundwater reported in driller's logs is associated with the tuff itself, or with overlying gravels. It is likely that the tuff underlying the valley was eroded and redistributed by the fluvial processes and the presence of agglutinated tuff represents areas that were relatively less affected by erosion. It is possible that in some areas, the Bishop Tuff is absent in the alluvial section due to complete removal by erosion, however its presence in boreholes throughout the study area suggests a fairly continuous sheet. Though the hydraulic parameters of the Bishop Tuff are uncertain, it is useful as a marker bed for delineating the subsidence of the Bishop basin.

The flat surface of the valley floor conceals considerable relief present in the basement rocks beneath the alluvial fill. Gravity studies show that south of Bishop, basement beneath the valley is asymmetrical, with the bedrock sloping to the east and the maximum thickness of about over 1,500 m (5000 ft) of Cenozoic basin fill lies just west of the White Mountain Fault Zone (Pakiser et al., 1964). A gravity high is present east of Fish Slough and north of Laws, suggesting that a bedrock horst may be present beneath the valley fill and Volcanic Tableland at a depth of possibly as little as 300 m (1000 ft) (Pakiser et al., 1964). An elongate gravity low extends from Bishop across the southern part of the Volcanic Tableland to the Owens Gorge, indicating that the southern part of the Tableland is underlain by low-density material, probably basin fill. The gentle gravity gradients underlying the Volcanic Tableland north of the Tungsten Hills suggests that the relief of the western part of the Volcanic Tableland resulted from warping or distributive faulting. A series of enechelon faults extends from south of Fish Slough south to the base of the Sierra Nevada near Rossi Hill, which corresponds to the eastern boundary of the gravity low. East of Bishop, the Bishop Tuff is apparently displaced west side down, suggesting that the basement may be down faulted to the west along this series of faults.

Quaternary faults in the study area affect groundwater flow in the study area. Faults may act as either barriers to flow across the plane of the fault (Williams, 1970), or conduits for flow within the plane of the fault (Rostaczer, 1987). Faults in the study area are in relatively unconsolidated material and steeply dipping, so they are treated here as low permeability barriers to horizontal flow. The USGS documents four fault zones within the study area that have Quaternary displacement: the range front faults bounding the Sierran Nevada and the White mountains, faults in the Volcanic Tableland, and the Fish Slough Fault Zone (USGS, 2006). Figure 2 suggests that the Sierran range front fault may be contiguous with the Fish Slough fault zone north of Bishop, however the west facing scarps of the Fish Slough faults and east facing scarp of the Sierran range front suggest opposite senses of dip slip on the two fault zones. Displacement of the Bishop Tuff observed in boreholes east of Bishop suggests that within the valley fill, dip slip along fault strand running from the Sierran range front to Fish Slough is west side down, similar to the sense of motion of the escarpment east of Fish Slough. The average strike of the four fault zones ranges from N10W to N4E. The density of fault scarps present on the surface of the Volcanic Tableland and on terraces south of the Owens River indicate that considerable Quaternary deformation is distributed across the Bishop basin. Slip rates for Quaternary faults in the Volcanic Tableland, Fish Slough area, and White Mountain fault zone are estimated to be 0.2 to 1.0 mm/year (0.008 to 0.04 in/yr), and 1.0 to 5.0 mm/year (0.04 to 0.2 in/yr) on the Owens Valley fault zone (USGS, 2006).

Aquifer System. The aquifer system in the study area consists of valley fill sediments and volcanic rocks. The general groundwater flow direction is from the north and west to the south, driven by recharge on upland mountain front and fan areas and discharge along the valley axis by phreatophytes, baseflow to the Owens River, and flowing wells. Though the valley-fill material is up to several thousand feet deep in the Bishop-Laws area (Pakiser et al., 1964), only the upper one thousand feet is relevant to groundwater management concerns. The basin fill deposits generally are coarse poorly sorted debris flow material at the base of the mountains, becoming finer and better sorted farther from the range fronts. The deposits in the center of the valley within the study area include extensive lacustrine deposits, which function hydraulically as confining layers in the groundwater system (Danskin, 1998). The lacustrine deposits pinch out laterally as the fluviolacustrine materials grade into alluvial fans, which behave as unconfined aquifers. Danskin (1998) developed aquifer units based on depositional settings, and a similar approach was used here, based on the geologic units shown in Figure 2. The effect of faulting on the aquifer system was represented either by discrete planar barriers to horizontal flow or by anisotropic hydraulic conductivity, depending on whether the faulting was in discrete zones or distributive.

Hydrologic Boundaries. The lateral boundaries of the aquifer system are where the valley-fill material contacts low-permeability mountain blocks. Though some groundwater undoubtedly flows through fractures in the bedrock of the mountain blocks, the higher permeability and storativity of the basin fill material motivates the assumption that the mountain blocks can be treated as regionally impermeable. Regions of low hydrologic stress, such as north of the Tungsten Hills and midway between Bishop and Big Pine, form the edge of the model domain where it is on the valley floor. This allows for constant head boundaries to be used in areas where natural hydrologic boundaries are absent.

Hydraulic Properties. Hydraulic conductivity has been estimated from 48 LADWP wells using various aquifer test methods (Danskin, 1998). The screened intervals of these wells are typically from about 20 to 100-200 m (100 to 330-660 ft). Hydraulic conductivity values from these wells are lognormally distributed and range from less that 1 m/day to over 100 m/day (3 ft/day to over 330 ft/day), with values typically being about 5 to 20 m/day (15 to 70 ft/day) (Figure 3). These wells are unevenly distributed in the study area, and the hydraulic testing of these wells is of uncertain and variable quality. It is evident from Figure 4 that the locations of aquifer tests have been mainly limited to the valley floor, and estimates from the Volcanic Tablelands and alluvial fans are absent.

To simplify the mathematical expression of groundwater flow, it is desirable that numerical model grids be oriented parallel to the principal directions of hydraulic conductivity (Anderson and Woesner, 1992). Numerical groundwater models for the Owens Valley (Danskin, 1998; Danskin, 1988) have oriented the model grid along an azimuth 345^{o}, parallel to the axis of the valley, on the assumption that regional geologic structure and topography control depositional environments which in turn control permeability anisotropy. For the present modeling effort, the model grid was oriented in a north-south direction, because in the Bishop Laws area, topographic and tectonic depressions in the study area are variously oriented east-west, north-south, and north-northwest-south-southeast. Major structure-bounding faults are predominantly oriented north-south and Quaternary fault zones strike north-south (Figure 2), and quaternary tectonism resulted in pervasive north striking fault scarp on the Volcanic Tablelands that are undoubtedly present in the valley fill to the south. These structural features are a likely source of regional-scale horizontal anisotropy, therefore the present model grid is oriented in a north-south direction.

Hydrologic Budget. Surface water features in the Bishop-Laws area include the Owens River and its tributaries; ditches that divert and return water to the Owens River and its tributaries; and ponds related to water treatment, recreation, or mining. The generally permeable nature of the valley fill results in linkage between surface water and groundwater. The Owens River, in the reach separating Laws and Bishop, can either gain or lose water depending on adjacent groundwater levels. Tributary streams traversing Sierran alluvial fans typically lose water, providing the major source of recharge in the study area. Canyons in the White Mountains have much smaller runoff volumes than the Sierran canyons. Silver and Coldwater Canyons are the only perennial streams issuing from the White Mountains. Although other canyons contain only ephemeral flows, localized heavy rainfall can produce high flows from these sparsely vegetated catchments with thin soils. Seepage from and extensive network of ditches and canals also provides recharge. Though current shallow groundwater levels are generally below the level of canal and ditch inverts, these conveyances potentially act as drains, limiting the maximum water table elevation. In this model, ditches were considered to act as sources of recharge.

Perennial ponds are present in the study area at Fish Slough (natural ponds resulting from spring discharge), a gravel mine near the center of the model domain (an excavation that intercepts the water table), the Bishop wastewater treatment plant, Buckley Ponds, and Mill Pond. Seasonal ponds maintained for waterfowl and shorebird habitat enhancement are also present north of Bishop (Farmer's Ponds) and near Laws (McNally Ponds). Flowing wells along the Owens River discharge 13,500 to 23,500 m^3/day (4,000 to 7,000 acre-foot/year) and support short reaches of paludal and riparian habitat between the wellheads and the river (Figure 5). During periods of high runoff, LADWP diverts water from the Owens River into groundwater recharge basins in the Laws area. The amount of water recharged in Laws varies widely depending on runoff availability. Between 1992 and 2005, artificial recharge in the Laws area has averaged 17,000 m^3/day (5,060 acre-foot/year), ranging from 0 to 105,000 m^3/day (0 to 31,077 acre-foot/year) (LADWP Totals and Means).

SIMULATION MODEL

Computer Code Description. The USGS Modflow groundwater modeling code was used to conduct the groundwater modeling (McDonald and Harbaugh, 1988). MODFLOW is widely used for modeling regional groundwater flow and has been used in previous modeling studies in the Bishop Laws area (Secor, 2004; Hutchison, 2001; Danskin, 1998; Radell, 1988). MODFLOW is a finite difference model with backward differencing in time, and has capabilities for simulating many hydrologic processes. Processes relevant to a particular problem can be simulated by including the applicable MODFLOW "package" in the simulation. For this study, the well package was used to simulate production wells, the river package was used to simulate the Owens River, the drain package was used to simulate flowing wells and spring discharge at Fish Slough, the recharge package was used to simulate mountain front recharge and recharge from stream channels and surface water conveyances, and the horizontal flow barrier package was used to simulate low-permeability faults. The Groundwater Vistas (Environmental Simulations, no year given) interface was used for developing model input, running and calibrating the model, and exporting and interpreting model output.

Assumptions and Limitations. The model developed here is intended to be used to assess the effect of hydrologic perturbations on ambient conditions. The steady-state represents ambient conditions, and the effect of perturbations is evaluated by modeling the change from steady-state provoked by the perturbation. The two transient scenarios presented here exemplify appropriate uses of the model: alterations in pumping amounts and patterns, and alterations in recharge. The appropriate use of this model is to evaluate the change in head or change in water budget components due to hydrologic perturbations. Although the model provides a reasonable rendition of the regional head field, it is unlikely to reproduce head or depth to water with enough accuracy at any given point to use it for hydroecological evaluations. In its current form, the model cannot be used to recreate historical fluctuations, however, such a transient model could be developed based on the present model.

Model Domain and Discretization. The southwest corner of the model domain is located at UTM zone 11 easting 365000 northing 4121000, and extends 33000 meters to the north and 25000 meters to the east. The model grid is oriented in the north-south/east-west directions. In the vertical direction, the model domain extends from the land surface to an elevation of 900 meters above sea level. Land surface elevations were taken from a USGS 10 m digital elevation model with a 1 m vertical resolution. The domain is discretized uniformly into a 132 x 100 cell grid of 250 x 250 m cells. The model has five layers; layers 1 through 4 are 50, 50, 75, and 100 m thick, and the fifth layer extends to the bottom of the model domain.

Hydraulic Parameters. The spatial distribution of hydraulic conductivity was based on the distribution of geologic units, aquifer tests on production wells, and both manual and automated model calibration. Hydraulic conductivity zones were developed by digitizing the geologic units shown in Figure 2, and assigning hydraulic conductivities to each zone. Table 1 lists the hydraulic conductivity zones used in the model. The spatial distribution of these zones is shown in Figures 6 through 10. The lower alluvial fan (zone 5) and lower Bishop Creek fan (zone 7) were modeled as anisotropic, with the north-south conductivity being greater than the east-west conductivity. The anisotropic conductivity reflects the pervasive north-striking faults that are present (Figure 11). Though these faults are often concealed on the valley floor, they undoubtedly are present at depth throughout much of the study area. Major fault zones were modeled as horizontal flow barriers (Figure 11). The range of hydraulic conductivities given in Table 1 is within the range of hydraulic conductivities estimated from aquifer tests of wells in the Bishop-Laws area (Figure 3). For transient simulations, the storage coefficient was assumed to be 0.1 in the upper model layer and 0.001 in the four lower model layers, similar to as was done by Danskin (1998).

Table 1. Hydraulic conductivity zones (m/day).

Zone #	Unit	K_x	K_y	K_z
1	Bishop Tuff	10	10	1
2	Till	1	1	1
3	Upper alluvial fan	10	10	1
4	Valley-center fluviolacustrine plain	10	10	0.1
5	Lower alluvial fan	10	15	1
6	Older valley fill	1	1	0.1
7	Bishop Creek lower alluvial fan	1	10	0.1

Sources and sinks. Recharge rates for stream channels and surface water conveyances were based on the rates used in Danskin's regional groundwater model (1998), which were based on loss rates determined from paired stream gauges and discussions with LADWP water managers. Some of the smaller recharge sources were either lumped together into a single recharge zone, or varied to achieve better calibration. The largest recharge sources, Bishop Creek and the McNally canals, used the same rates as Danskin's (1998) model. Irrigation return flow recharge was assumed to occur at a rate of 0.000435 m/day (6 inches/year). A recharge rate of 0.0003 m/day (4 inches/year) was assumed for the upper Volcanic Tablelands; this rate is uncertain, and arbitrary, since the actual area and volume of net recharge on the Volcanic Tablelands, and underflow from Long Valley are unknown. This rate represents those combined unknown recharge rates. Model recharge zones are shown in Figure 12. Evapotranspiration (ET) zones were assigned based on LADWP's maps of vegetation types Los Angeles owned land and by digitizing areas of phreatophytes from aerial photographs. A maximum ET rate of 0.00411 m/day (5 ft/year), which is equal to the potential ET rate for Bishop (CIMIS, 2003), was used for all ET zones. An extinction depth of 7 m (23 ft) was used for all ET zones. This extinction depth is somewhat deeper than the nominal root zone of phreatophytic grasses (2 m, 6.6 ft) and shrubs (4 m, 13.1 ft), but is comparable to root zones for larger phreatophytes such as cottonwoods and willow trees.

Table 2. Recharge zones and rates (m/day or ft/yr in parentheses).

Zone #	Recharge source	Recharge rate	USGS model rate
2	Irrigation return	0.000435 (0.52)	---------
3	Fish Slough	0.00093 (1.11)	0.00093
4	Silver Canyon	0.02000 (23.96)	0.00114
5	Shannon Canyon	0.00278 (3.33)	0.00278
6	Birch Creek	0.00050 (5.99)	0.00588
7	McGee Creek	0.01200 (14.37)	0.00403
8	Horton/Rawson/Freeman	0.00261 (3.13)	0.00256-0.00261
9	Bishop Creek	0.02934 (35.10)	0.02934
10	McNally Canals	0.00700 (8.39)	0.00669-0.00711
11	Bishop ditches	0.00003 (0.036)	0.0039-0.0069
12	White Mtn. range front	0.00009 (0.11)	0.000030
13	Tungsten Hills range front	0.00040 (0.47)	0.000321
14	Sierra Range Front	0.00040 (0.47)	0.000321
15	Upper Tablelands	0.00030 (0.35)	---------

Most of the pumping capacity in the study area is from LADWP wells that are used for use by the town of Laws, export to the City of Los Angeles, irrigation of LADWP leases, and for various mitigation and habitat enhancement projects. The City of Bishop operates wells for municipal supply. Additionally, several community service district, tribal, and private domestic wells pump relatively small amounts of water. In this model, only LADWP and City of Bishop wells are considered, because of their relatively greater pumpage (Table 3). Groundwater withdrawal was distributed among model layers based on the layer transmissivity and screened interval of each well. This generally resulted in wells producing from model layers 1 through 4, except for wells W387, W388, and W412 which produced from layers 2 through 4. For the steady-state model, pumping rates were the average rate for 2003, 2004, and 2005. The pumping rate for all production wells in the steady-state model was 54,734 m^3/day (22.4 cfs).

Table 3. Pumping rates for production wells, 2003 – 2005 average (m^3/day or cfs in parentheses).

Bishop		Laws	
Well	Rate	Well	Rate
W140	4352 (1.8)	W236	4434 (1.8)
W371	4218 (1.7)	W239	1959 (0.8)
W406	3203 (1.3)	W244	2277 (0.9)
W407	2593 (1.1)	W245	664 (0.3)
W408	3931 (1.6)	W247	1209 (0.5)
W410	7307 (3.0)	W354	97 (0.04)
W411	6015 (2.5)	W365	2022 (0.8)
W412	3079 (1.3)	W377	6 (0.0)
Bishop #2	1515 (0.6)	W387	3179 (1.3)
Bishop #4	114 (0.05)	W388	2560 (1.0)

Flowing wells along the Owens River (Figure 14) discharged an average of 16,088 m^3/day (6.57 cfs) over the period 1996-2005 (Table 4). These wells were modeled using the MODFLOW drain package, which requires specification of a drain elevation and conductance. Elevations are given in Table 4, and all were assigned a conductance of 10,000 m^2/day. Different averaging periods were used for the pumped versus flowing wells because the operation of pumped wells has changed recently as new wells have come on-line; the chosen periods exemplify recent steady-state conditions.

Table 4. Flowing well discharge, 1996 – 2005 average (m^3/day or cfs in parentheses)

Well	Discharge	Drain elevation (m amsl)
F121	95 (0.04)	1215
F122	334 (0.14)	1220
F123	0 (0.00)	1224
F124	959 (0.39)	1227
F125	3116 (1.27)	1231
F126	915 (0.37)	1230
F127	1354 (0.55)	1227
F128	1050 (0.43)	1224
F129	304 (0.12)	1224
F131	3764 (1.54)	1234
F132	986 (0.40)	1239
F133	1323 (0.54)	1240
F134	2299 (0.94)	1237
F136	479 (0.20)	1236
Total	16,088 (6.57)	

Table 5. Water budget for steady-state model (m^3/day, for acre-feet/year, divide by 3.376)).

Source/Sink	Inflow	Outflow	Net
Well	0	-54,734	-54,734
Constant head bdy.	155,511	-59,935	95,576
River	82,181	-178,681	-96,500
Drain	0	-20,897	-20,897
Recharge	339,992	0	339,992
Evapotranspiration	0	-263,882	-263,882
Total	577,685	-577,730	-45 (-0.00779%)

Boundary Conditions. Constant head boundaries were used to simulate areas of underflow within valley fill. Constant head boundary conditions were assigned in the area of Pleasant Valley Dam at the western boundary, at Chalfant Valley on the northern boundary, and in the valley fill at the southern boundary (Figure 14). Head-dependent boundary conditions were used to simulate the Owens River using the MODFLOW river package, and to simulate flowing wells along the Owens River and springs at Fish Slough using the MODFLOW drain package (Figure 14). For the Owens River, the starting and ending elevations of seven river reaches were determined from the digital elevation model. The river stage was set at 1 m (3.3 ft) below the land surface, river depth at 2 m (6.6 m), river width at 4 m (13.2 ft), river bottom thickness at 2 m (6.6 ft), and streambed hydraulic conductivity set at 2 m/day (6.6 ft/day).

Sensitivity Analysis. Sensitivity analyses were conducted twice during development of the model. Prior to calibration, sensitivity analysis was done to determine which parameters were most sensitive. Efficacious model calibration requires that only sensitive parameters be varied during calibration, whether calibration is done manually or automatically, because varying insensitive parameters during calibration can result in non-unique or ineffective calibration. After the steady-state model was calibrated, sensitivity analysis was redone to determine the sensitivity of the final parameterization of the model. Both sensitivity analyses showed that the most sensitive parameters were horizontal hydraulic conductivity of the clastic fill of the valley-center and lower alluvial fans. Vertical hydraulic conductivity, glacial till, and conductivity of the Bishop Tuff are relatively insensitive parameters. Recharge zones with the highest recharge rates were more sensitive than zones with lower rates. This is partly because sensitivity analyses are carried out by making multiplicative changes to parameter values, and applying a multiplicative change to a larger rate results in a relatively larger perturbation to the overall water budget, and partly because the higher rate recharge zones generally contribute more to the water budget.

Calibration. Primary calibration targets were April 2006 water level elevations developed from LADWP test well data (Appendix 1). Additionally, the modeled total discharge of flowing wells along the Owens River was matched to observations, and the whole-model water balance constrained the model to not allow unreasonably large amounts of water to discharge to the Owens River. The primary calibration goal was to have the ratio of the standard deviation of the residuals to the overall range in calibration targets be less than 0.05. Calibration of the model achieved a ratio of 0.029.

Hydraulic conductivity values were varied for zones 4 and 5, recharge zones, and ET rates were varied systematically to achieve an optimal the match between observed and modeled head targets. Automatic calibration resulted in recharge rates that were unreasonably high and baseflow to the Owen River that was unreasonably large, so recharge rates were returned to their original values and only hydraulic conductivity values were varied. Finally, manual calibration of anisotropic hydraulic conductivity produced the parameters in Table 1 and the calibration results in Table 6. During each calibration step, conductances of flowing wells along the Owens River were adjusted to achieve an approximate match between observed and modeled total flowing well discharge.

The overall match between observations and model results was close to linear (Figure 15), and the distribution of the residuals was roughly symmetric (Figure 16). It is clear from Appendix 1 and Figure 15 that the majority of calibration targets were in layer 1, with very few below layer 2 and none below layer 3. Spatial correlation between residuals is evident in Figure 17, with areas of model overestimate south, west, and north of Bishop, and areas of model under estimate east of Laws. It is apparent from Figure 17 that the river boundary condition constrains the model to produce results close to observations south of Laws, but does not provide similar results along the river north of Bishop.

Table 6. Calibration statistics of steady-state model.

Residual Mean	-1.77
Residual Standard Deviation	3.85
Sum of Squares	2245.4
Absolute Residual Mean	3.34
Minimum Residual	-10.56
Maximum Residual	15.21
Range	131.69
Standard Deviation/Range	0.029

PREDICTIVE SIMULATIONS

Two predictive simulations were conducted to apply the model to current water management issues. The first issue is the construction and operation of new wells by LADWP; the second issue relates to reductions in recharge due to alterations in surface water management.

New wells. The new wells that were evaluated here were approved in the Plan and environmental documentation has been prepared for them, however the Plan still requires that new wells be evaluated, preferably with a groundwater model, prior to operation, in order to guide the design of a management protocol for operation of the well (Los Angeles and Inyo County, 1991). The locations and capacities of the new wells are given in the Environmental Impact Report for the Plan (Los Angeles and Inyo County, 1990). The two new wells in the Laws wellfield are expected to produce 22,036 m^3/day (9.0 cfs) and the five new wells in the Bishop area are expected to product 45,296 m^3/day (18.5 cfs). For the predictive transient model, these rates were divided equally between each well in their respective wellfields.

Figure 18 shows drawdown contours resulting from operation of the new wells at full capacity for three years. Maximum drawdowns of over 5 m (16.5 ft) center on the production wells, and of over 1 m occur at distances as great as 5 km (3 miles) from the pumping wells. The Owens River acts as a buffer to the expansion of the cones of depression from both wellfields. Baseflow to the Owens River decreased by 71% after four years of pumping, flowing well discharge decreased by 18%, and ET decreased by 13%. The relative effects on baseflow, flowing well discharge, and ET depend on the degree of hydraulic communication between the groundwater system and the river, the conductance and source-depth of flowing wells, and the effective rooting depth of phreatophytes. Figure 19 shows drawdown hydrographs at several native vegetation parcels in the Bishop area. Nominal rooting depths for such parcels are 2 and 4 m (6.6 and 13.1 ft) for meadow and scrub parcels respectively; it is clear that drawdowns of the magnitudes shown in Figure 19 could significantly affect water availability in the root zone of native phreatophytes. In this model, a high degree of communication between the groundwater system and the river is assumed, which resulted in baseflow capture as the primary water budget alteration induced by the increased pumping. If the groundwater system is more isolated from the river than assumed here, the cones of depression shown in Figure 18 would be larger in extent and depth, and the decrease in ET would be greater. In 1940, Inyo Superior Court decreed that LADWP's combined groundwater pumping and flowing well discharge shall not exceed water uses on LADWP's lands (Hillside Water Company vs. City of Los Angeles). Due to this court-decreed limitation on LADWP's pumping in the Bishop area, pumping rates such as those modeled here would require a commensurate increase in irrigation on LADWP's leases in the Bishop area. This would result in greater irrigation return flows to the shallow groundwater system, however such changes in irrigation-induced recharge were not considered here.

Operation of the McNally Canals. Operation of the McNally Canals in the Laws wellfield has been a subject of dispute between Los Angeles and Inyo County. The canals have been operated intermittently for over 100 years to divert water from the Owens River for irrigation and artificial recharge in the Laws area, and shallow groundwater levels have varied accordingly. The Plan requires that LADWP operate its surface water conveyances in accordance with past practices since 1970. In 2001, Inyo County asserted that LADWP's past and continued reduction in diversions into the McNally Canals without proper approval was contrary to the surface water provisions of the Plan, and initiated a formal dispute resolution process. The issue was ultimately remanded to the technical staffs of the County and LADWP, and remains there unresolved. The impact of reduced flows in the McNally Canals on the water table in Laws remains a key issue in this dispute.

The model was used to assess the effect of discontinuing flows in the McNally Canals, and discontinuing water spreading activities in the western part of the Laws area. The steady-state model posits 60,812 m^3/day (24.8 cfs) of recharge from the McNally Canals; for this scenario, recharge from the McNally Canals was reduced to 0 m^3/day. Figure 20 shows how the water table declines under three phreatophytic vegetation parcels in the Laws area when canal flows are discontinued. Parcel LAW052 is closest to the canals, and consequently sustains the largest decrease in water level. In all three parcels, the rate of decline diminished after two or three years, which is similar to the pattern of decline observed in shallow monitoring wells in Laws. This similarity provides a qualitative verification that the model is rendering transient effects in a reasonable fashion. Lowering of the water table resulted in a 12% decrease in ET in the vicinity of the vegetation parcels identified above, and a 17% reduction in baseflow to the Owens River. Figure 21 shows that the extent of effects on the water table due to no flow in the McNally Canals. Translating these changes into impacts on phreatophytic vegetation is beyond the scope of this report, however it is noteworthy that routine reinventories of native vegetation in these three parcels has shown that perennial vegetation cover has declined since baseline vegetation conditions were assessed in the mid-1980's. This transient run represents drawdown from a steady-state condition, so it should not be interpreted as a recreation of changes since mid-1980's; rather, it is representative of potential changes caused by cessation of canal operations.

SUMMARY AND CONCLUSIONS

A steady-state numerical groundwater model for the Bishop-Laws area was developed based on a conceptual model incorporating the study area's geologic materials, tectonic setting, and surface water hydrology. The steady-state model was used to generate initial conditions for two transient applications of the model. The first transient application of the model determined the amount of drawdown that would be caused by full operation of new production wells that have been proposed for construction. The second transient scenario looked at how water levels change when canal operations are reduced in Laws. These two applications are relevant to recent groundwater that LADWP and Inyo County have joint responsibility for managing.

The steady-state model was calibrated to recent hydrologic conditions. Both manual and automated calibration were used to achieve an overall calibration where the residual standard deviation was 2.9% of the range in target heads. Additionally, discharge from flowing wells and water balance components were used in the calibration process to ensure that the model was a reproducing the hydrology of the study area.

LADWP plans to install seven new wells in the Bishop-Laws area. Locations and approximate capacities of these wells are given in City of Los Angeles and County of Inyo (1990). Modeling of full operation of these wells indicated that they would develop an extensive cone of depression up to about 5.0 m near wells. A court decree limits LADWP pumping and flowing well discharge in the Bishop area to not greater than the amount of water used on LADWP lands in the area. In the past, this court decree has been considered adequate to limit pumping near Bishop, and none of the management constraints applied elsewhere in the Owens Valley have been implemented in Bishop. Because the proposed new wells could result drawdowns that could cause impacts to native vegetation, additional management of groundwater pumping in the Bishop area may be necessary in the future.

The model was used to determine the effect of the McNally Canals on the water table in Laws. Operation of these canals has been a point of dispute between LADWP and Inyo County, which centered on whether diminished use of the canals to move water into Laws was reducing the amount of water available for native phreatophytic vegetation (James, 2001). Reducing recharge from the McNally Canals resulted in the reductions in water table elevation of up to 4 m beneath parcels of groundwater dependent vegetation.

The model developed for this study was designed flexibly so that it can be applied to water management issues in the future. While the applications described above are relevant to current groundwater management problems, their purpose here was primarily as heuristic explorations of the utility and flexibility of the model. The Groundwater Vistas graphical user interface allowed the transient applications to be efficiently developed from the steady-state model, and model output to be easily extracted and interpreted. Because the model was developed within the Inyo County Water Department, future applications can be developed in-house. Desirable future developments of the model include development of a time-series of historical inputs for transient modeling, verification of water budget quantities such as baseflows to the Owens River and channel seepage losses, and development of validation data to increase confidence in the model.

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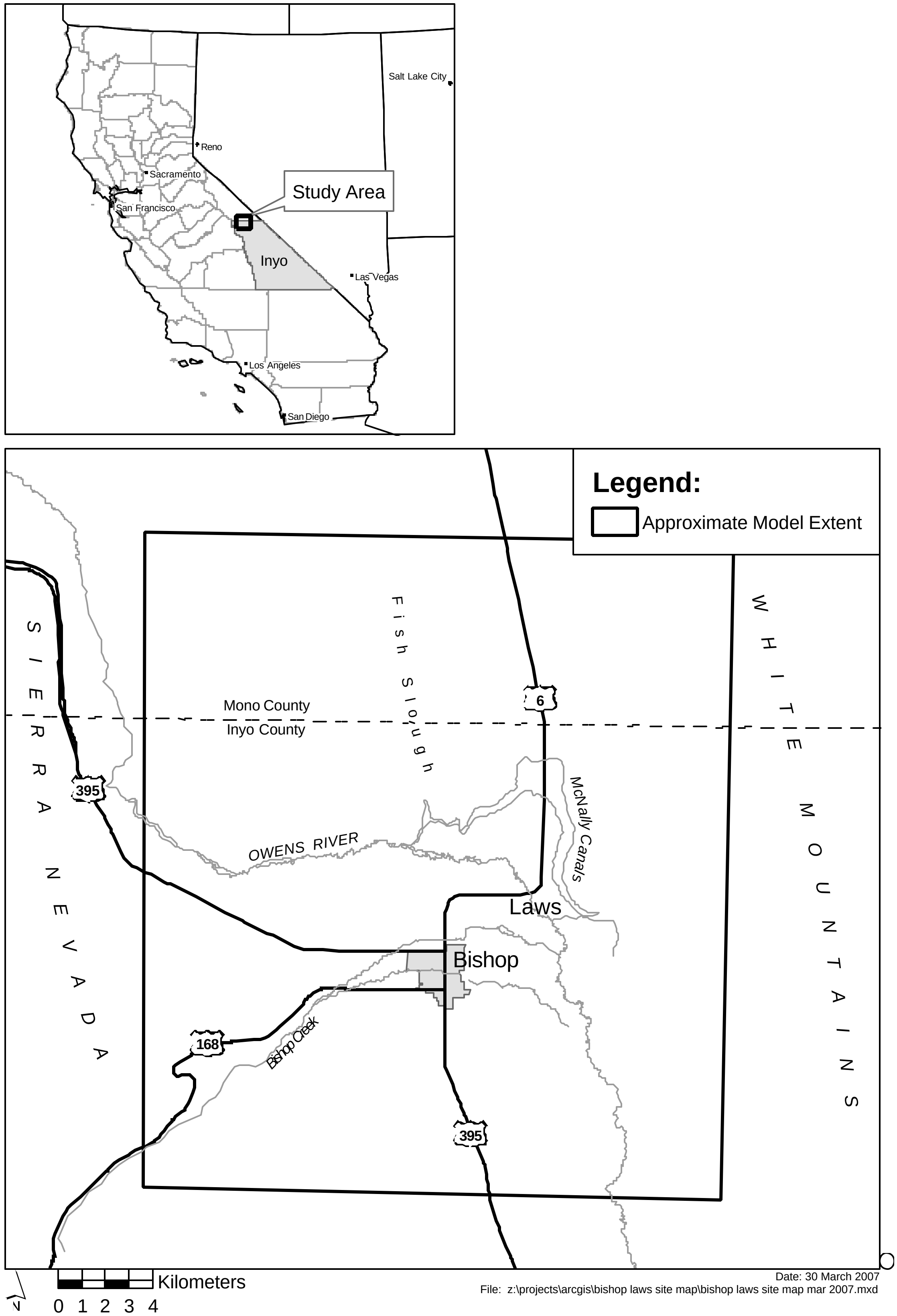

Figure 1. Location of study area.

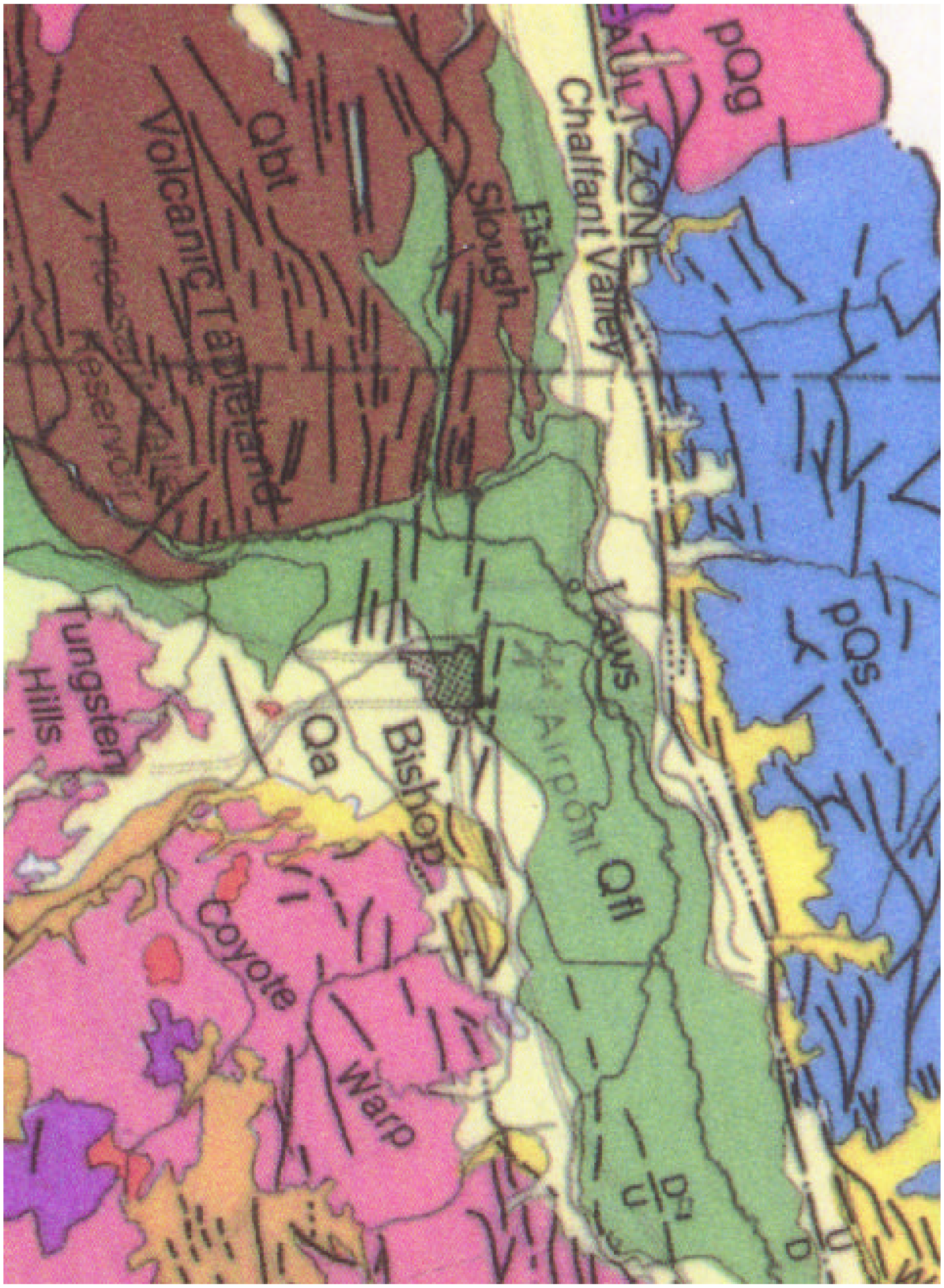

Figure 2. Geology of the Bishop-Laws area. Qa: Quaternary alluvium; Qfl: Quaternary fluviolacustrine deposits; Qbt: Bishop Tuff; pQg: pre-quaternary granitic rocks; pQs: pre-quaternary sedimentary rocks. Also shown are Quaternary till (light brown), Quaternary older fan (yellow), and Quaternary basalt (red) (from Hollett et al., 1991).

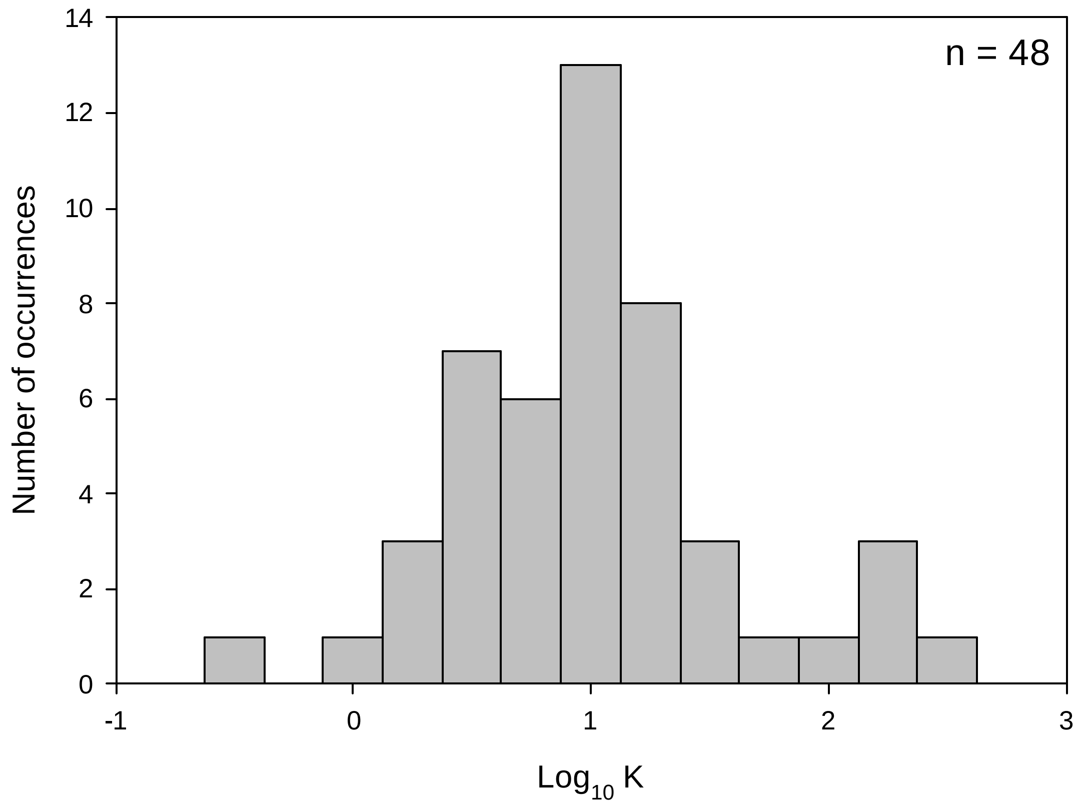

Figure 3. Distribution of logarithms of hydraulic conductivity (m/day) from aquifer tests of LADWP production and flowing wells.

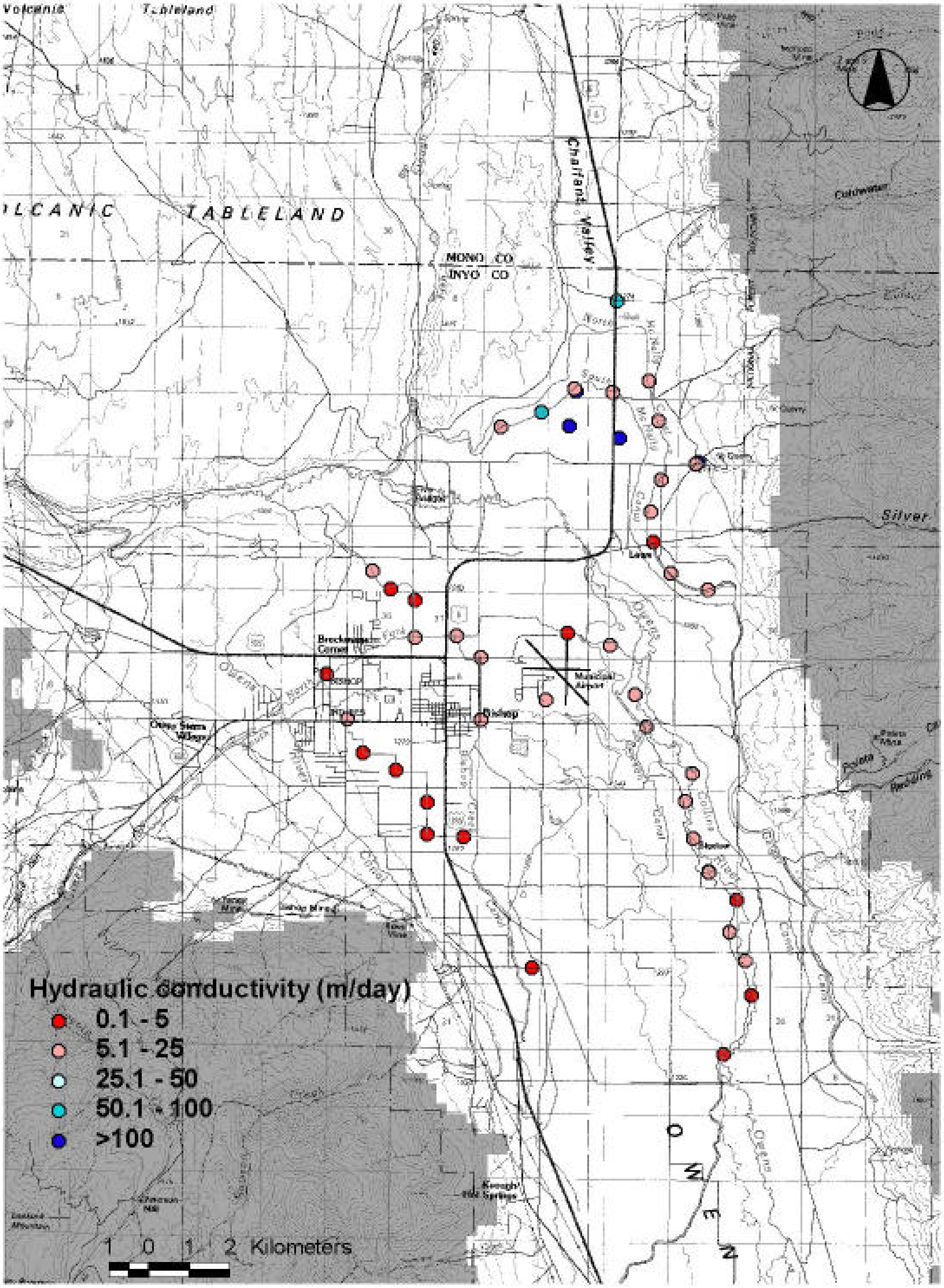

Figure 4. Hydraulic conductivity (m/day) estimated from aquifer tests.

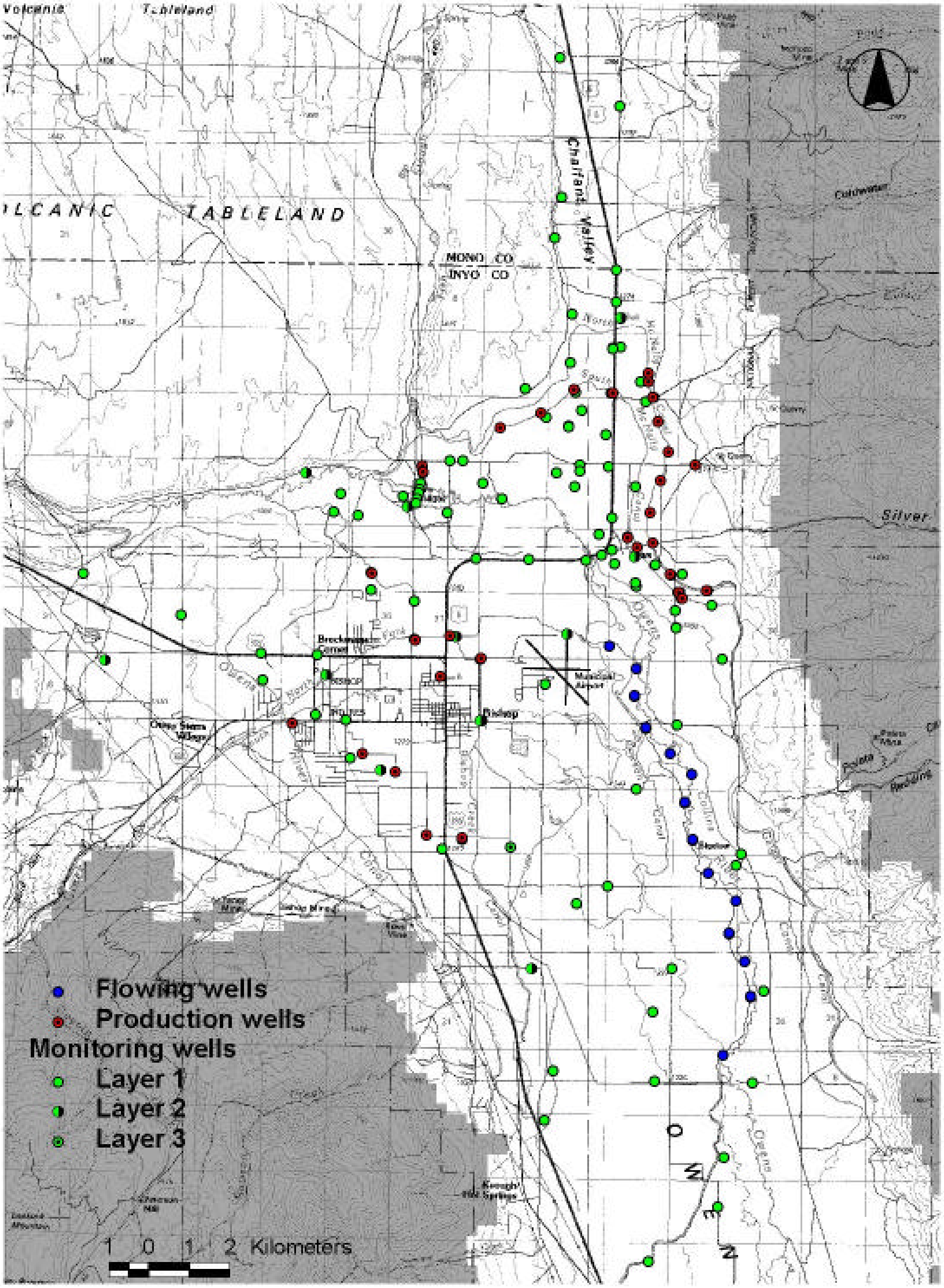

Figure 5. Wells in the Bishop-Laws area. No-flow cells are grey.

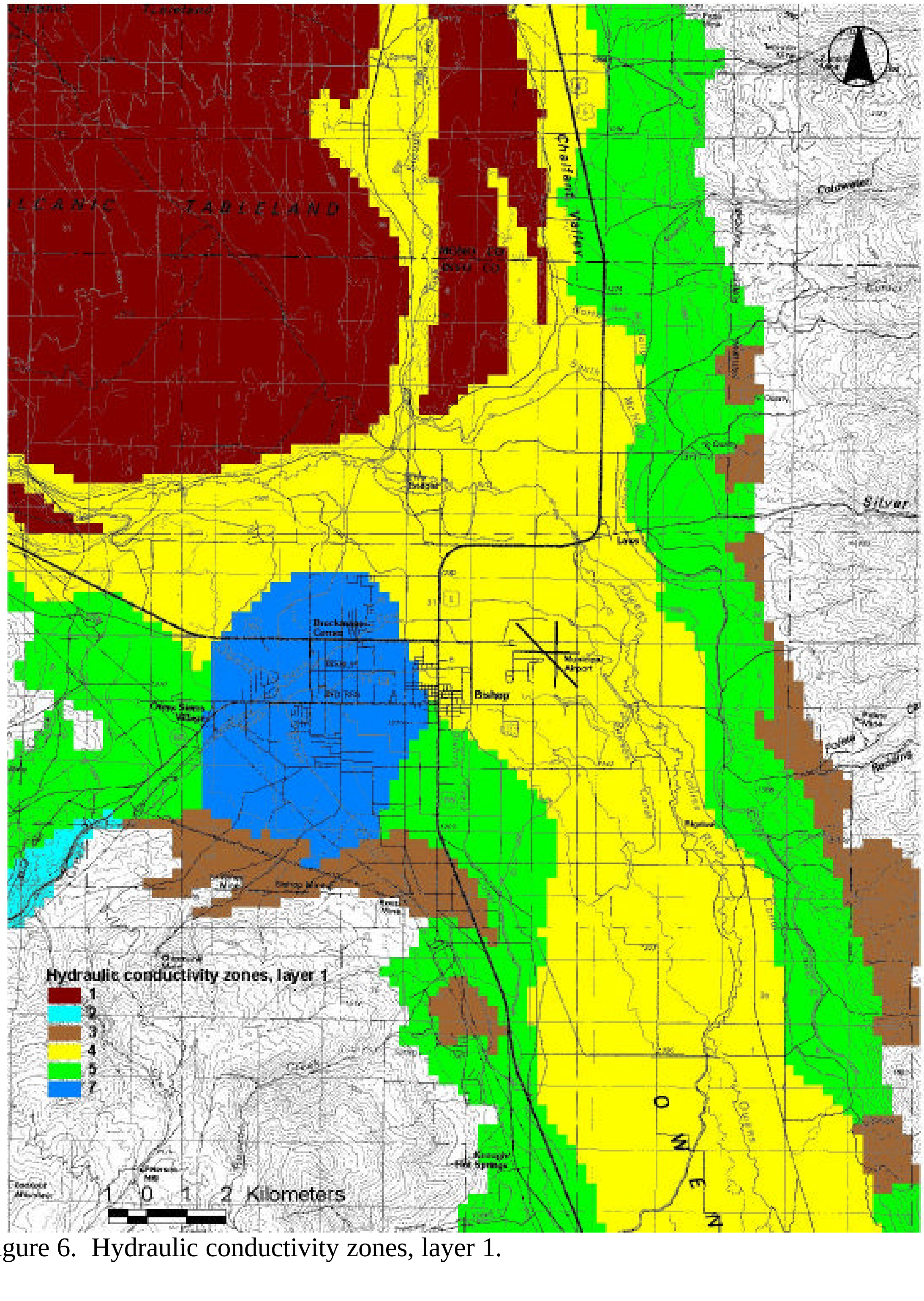

Figure 6. Hydraulic conductivity zones, layer 1.

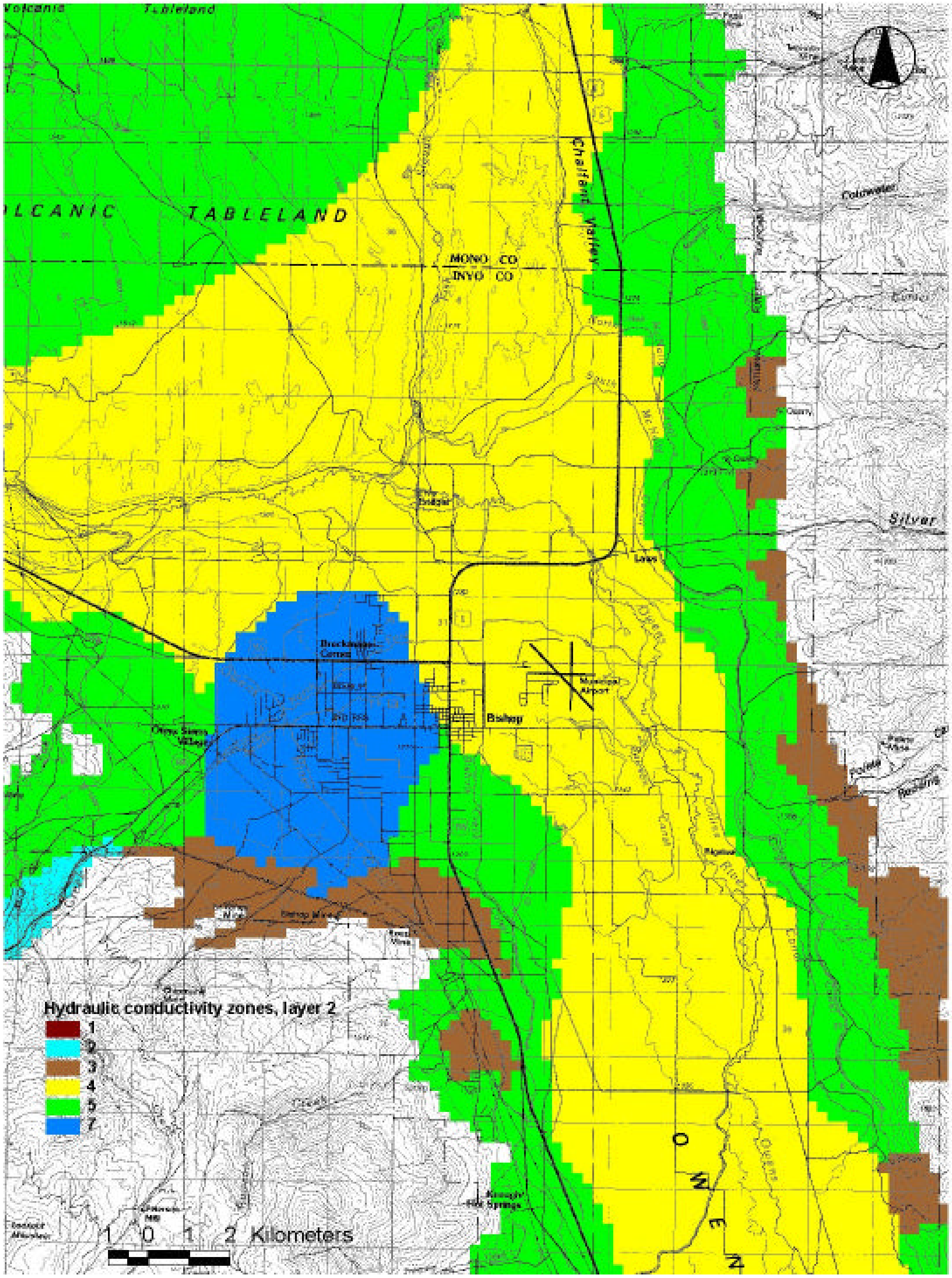

Figure 7. Hydraulic conductivity zones, layer 2.

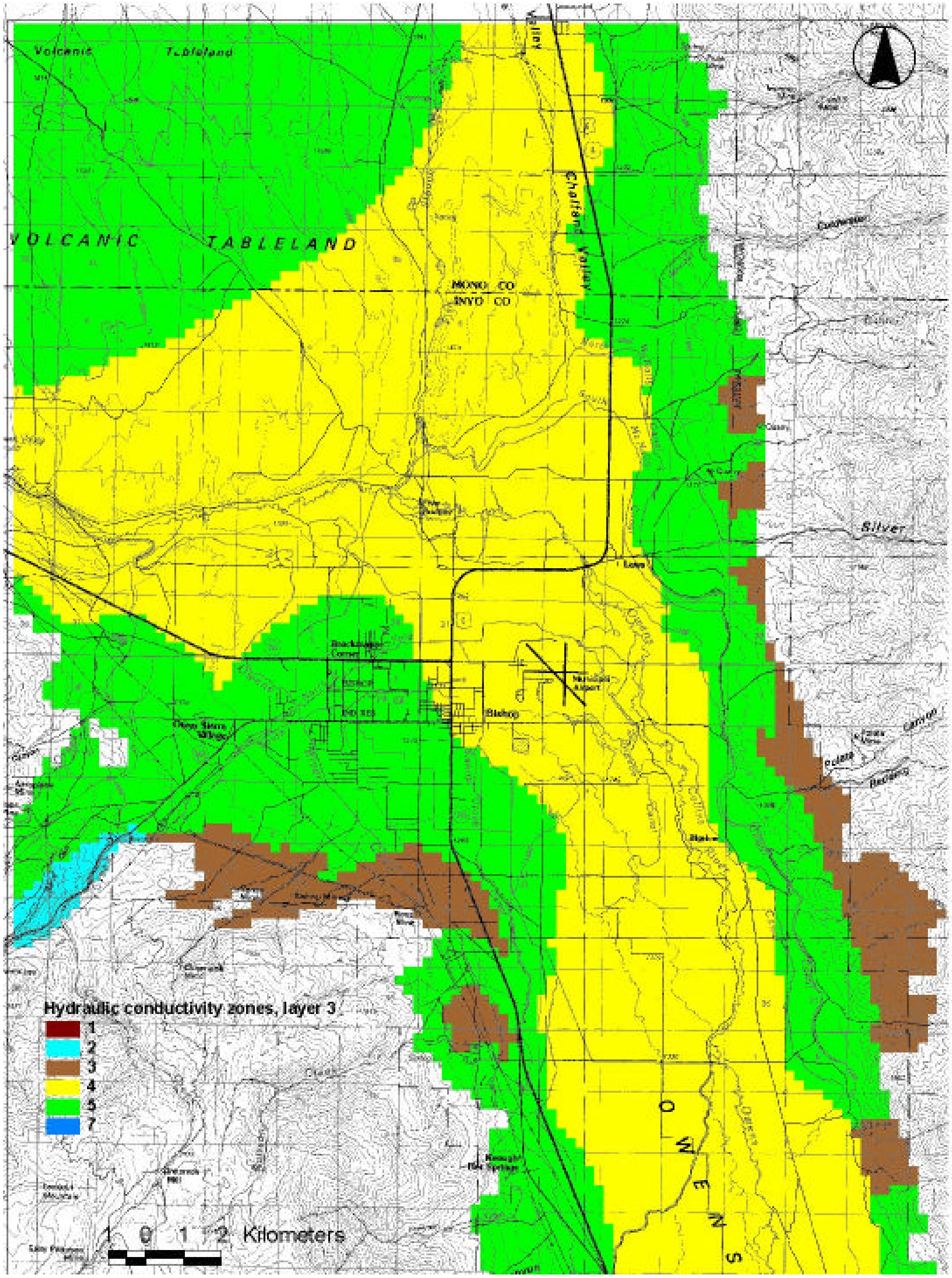

Figure 8. Hydraulic conductivity zones, layer 3.

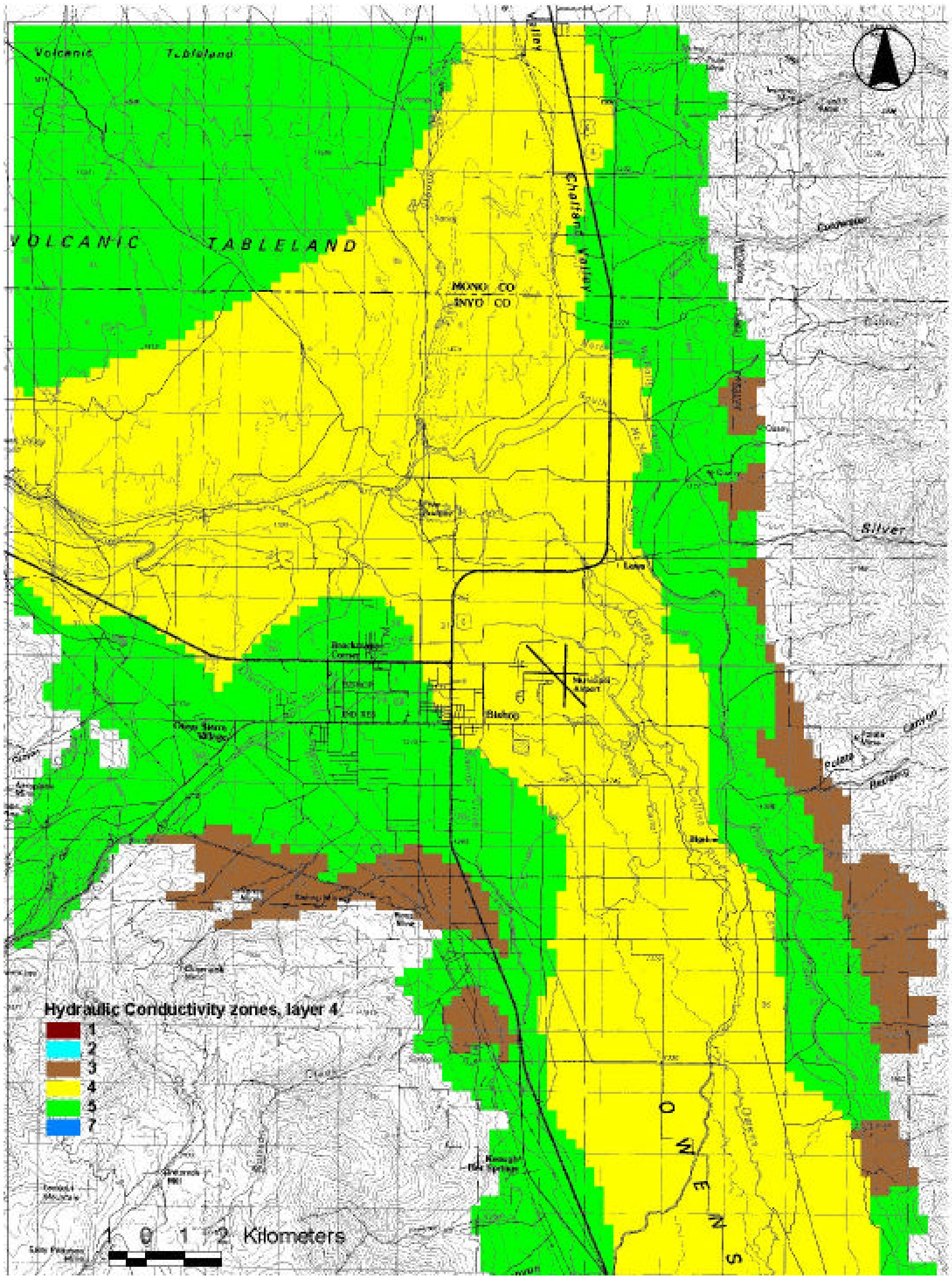

Figure 9. Hydraulic conductivity zones, layer 4.

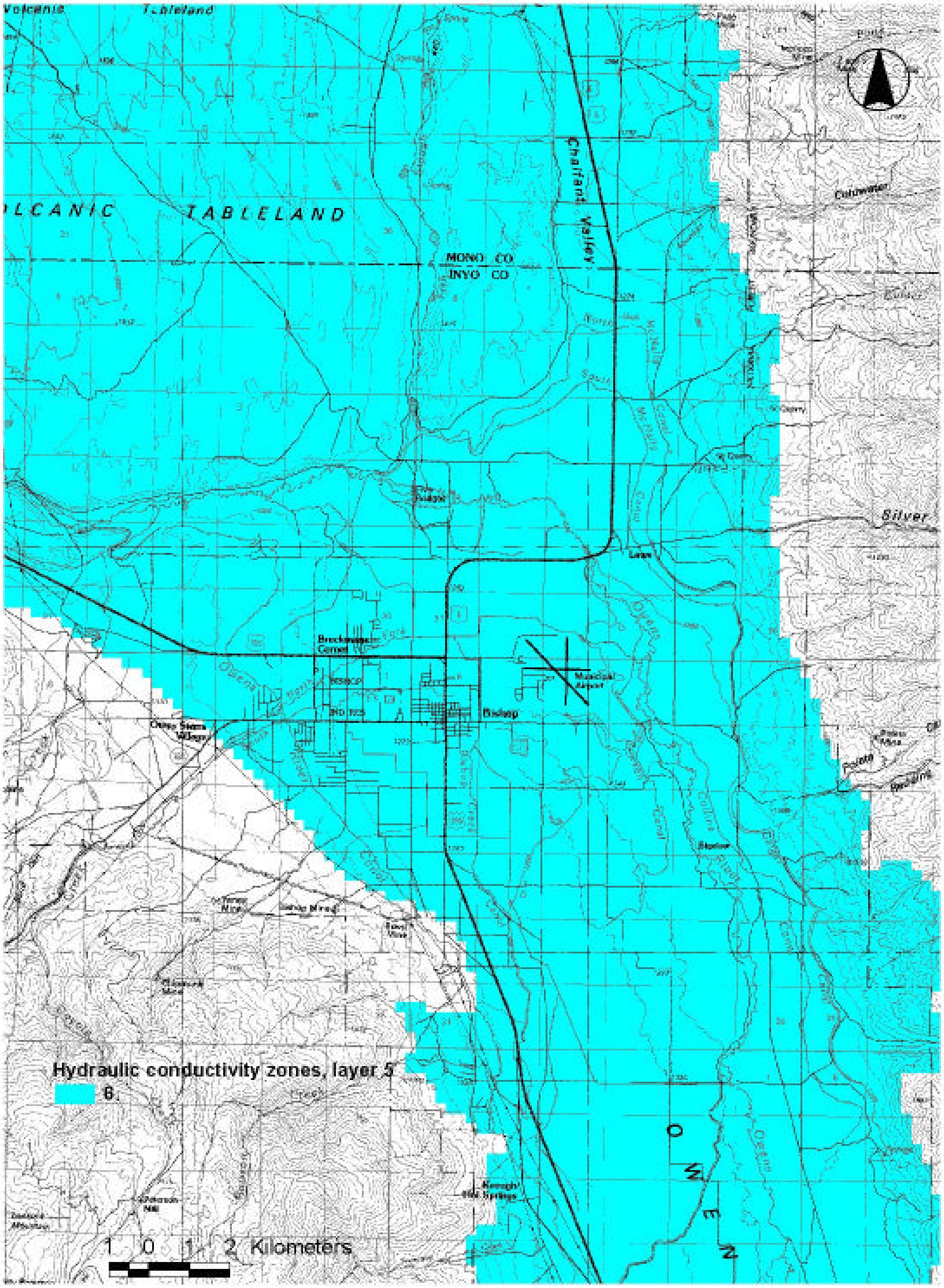

Figure 10. Hydraulic conductivity zones, layer 5.

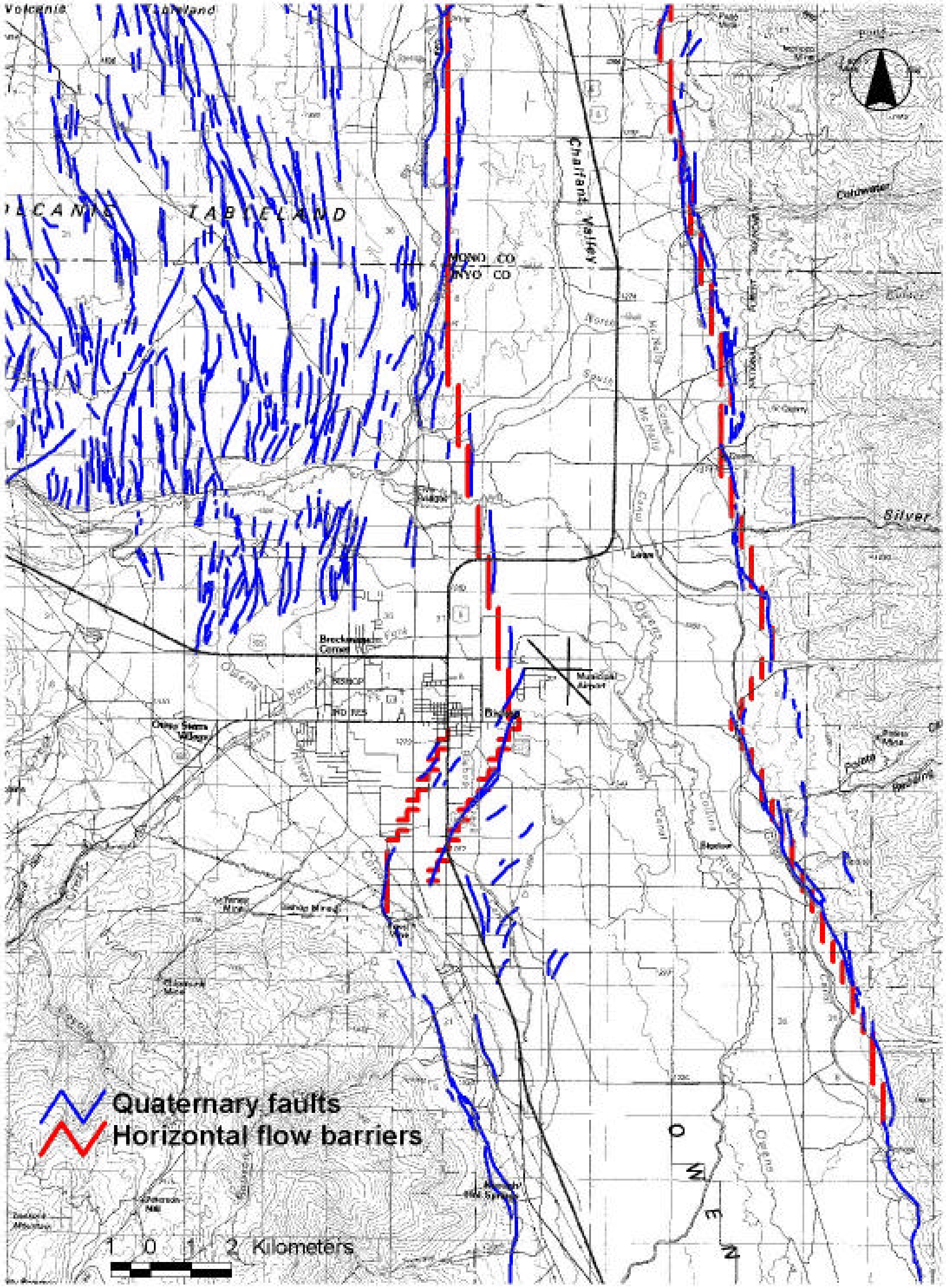

Figure 11. Quaternary faults (USGS, 2006) and modeled horizontal flow barriers.

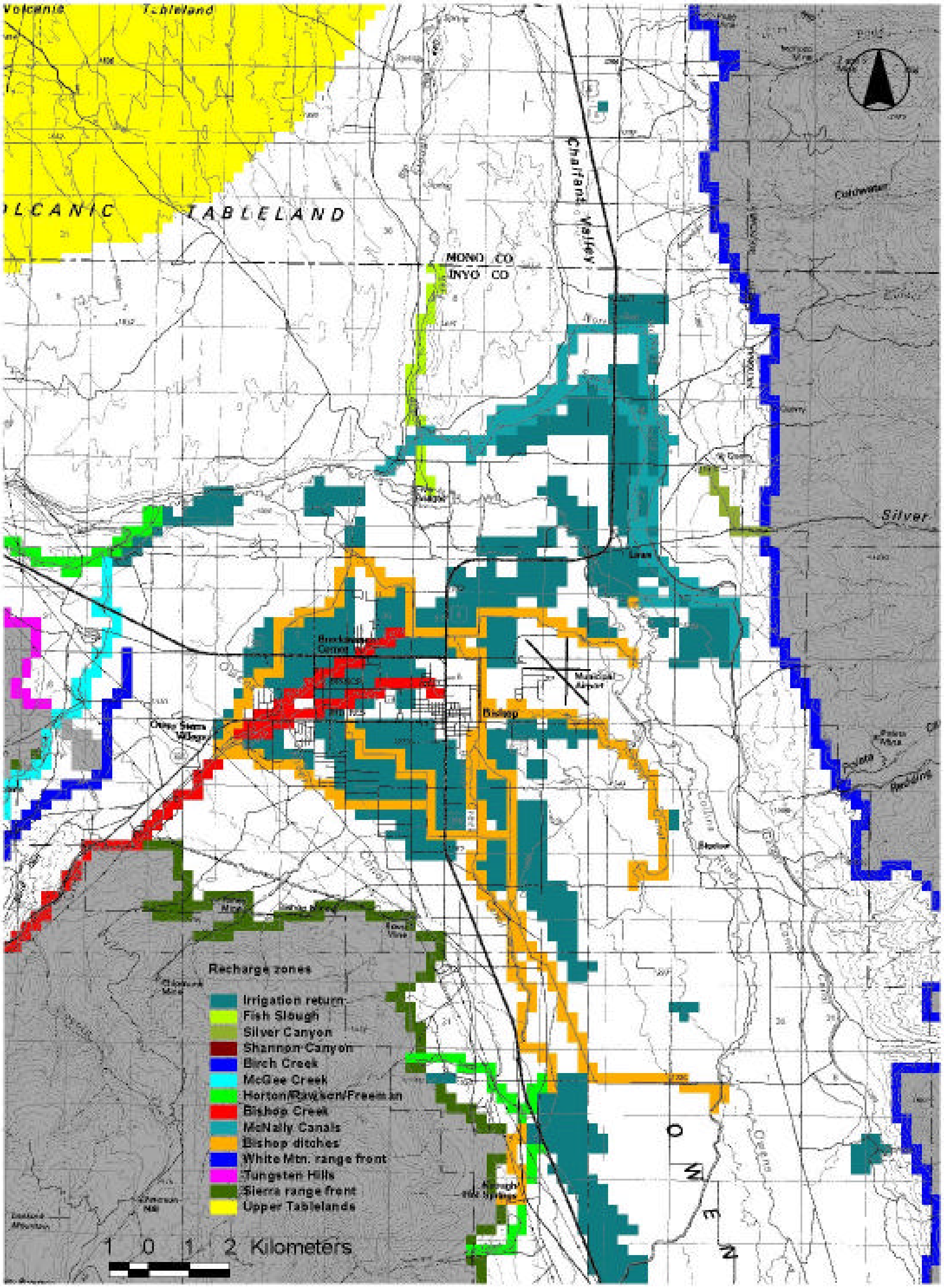

Figure 12. Recharge zones. Grey areas are inactive cells.

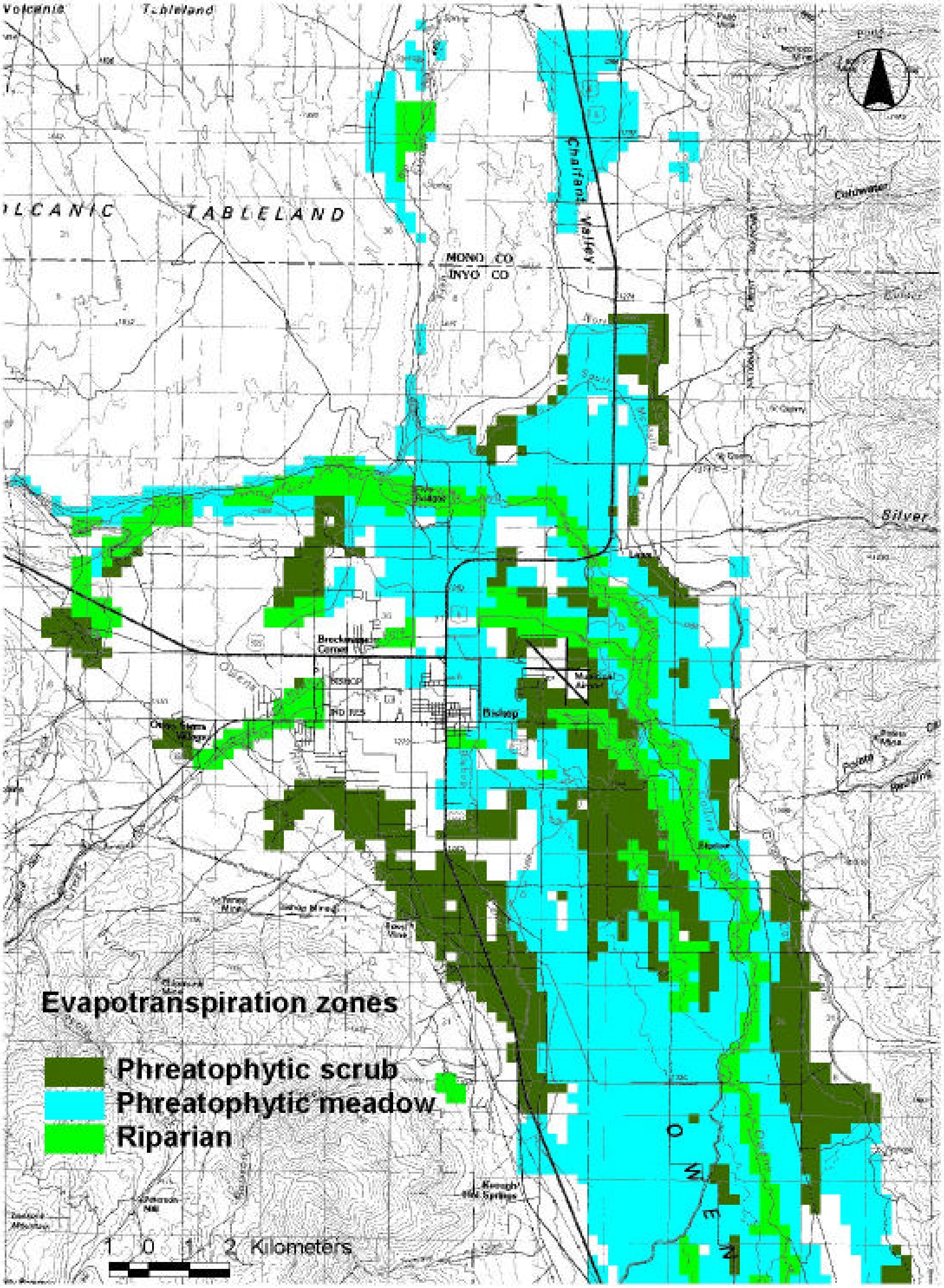

Figure 13. Evapotranspiration zones.

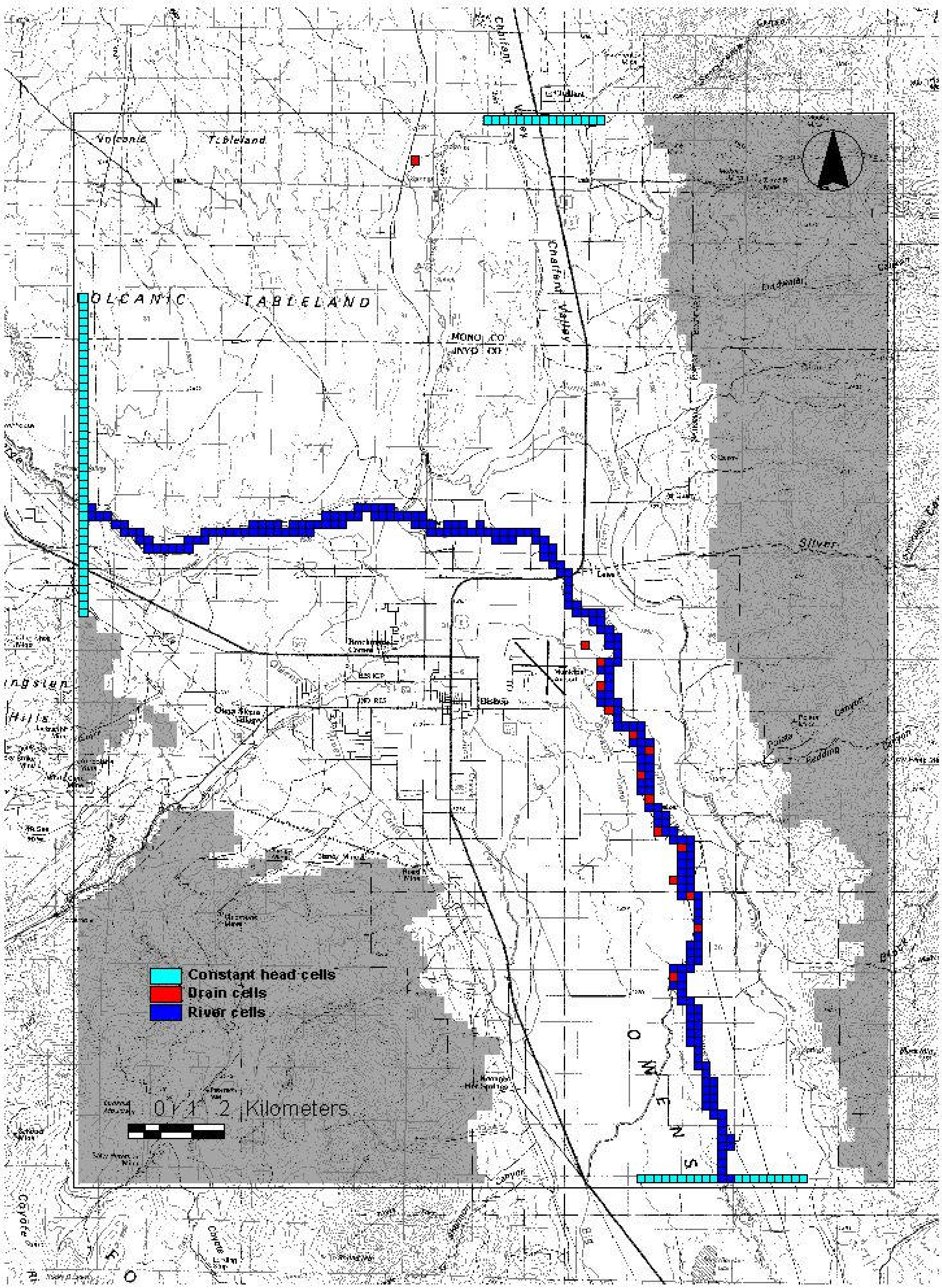

Figure 14. Boundary conditions. Drain cells along Owens River are in layer 3; drain at Fish Slough is in layer 1. Constant head cells extend through all layers.

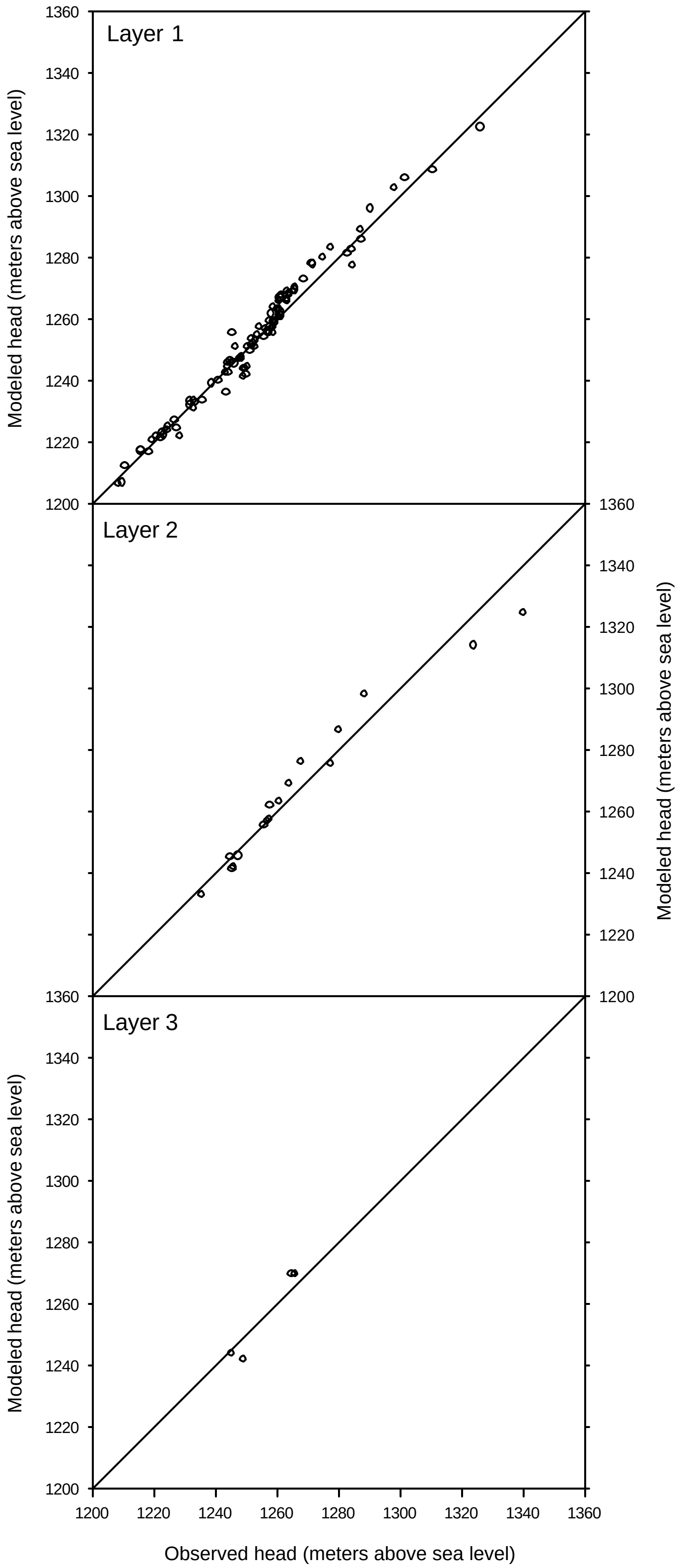

Figure 15. Observed versus modeled head in model layers 1 through 3. 1:1 line is shown.

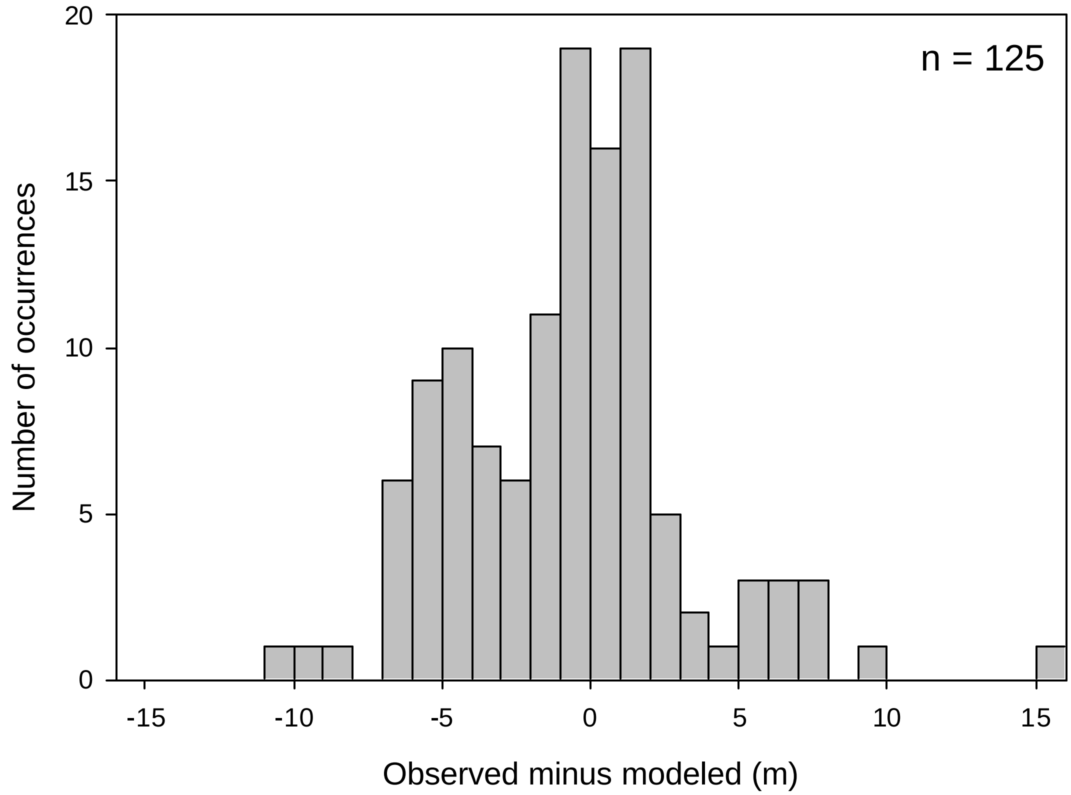

Figure 16. Distribution of calibration residuals. Bin width is 1 m.

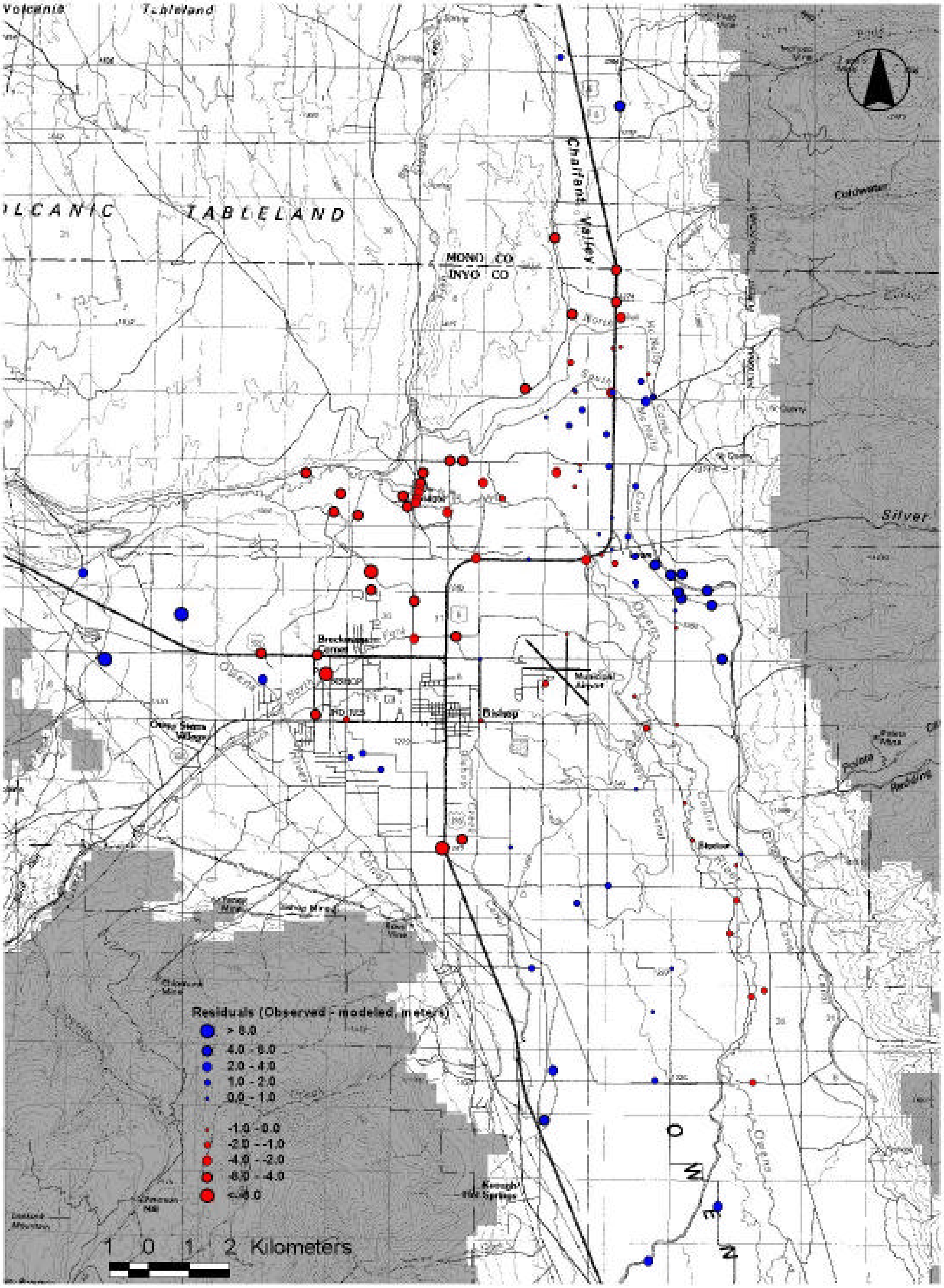

Figure 17. Residual values (observed minus modeled, m).

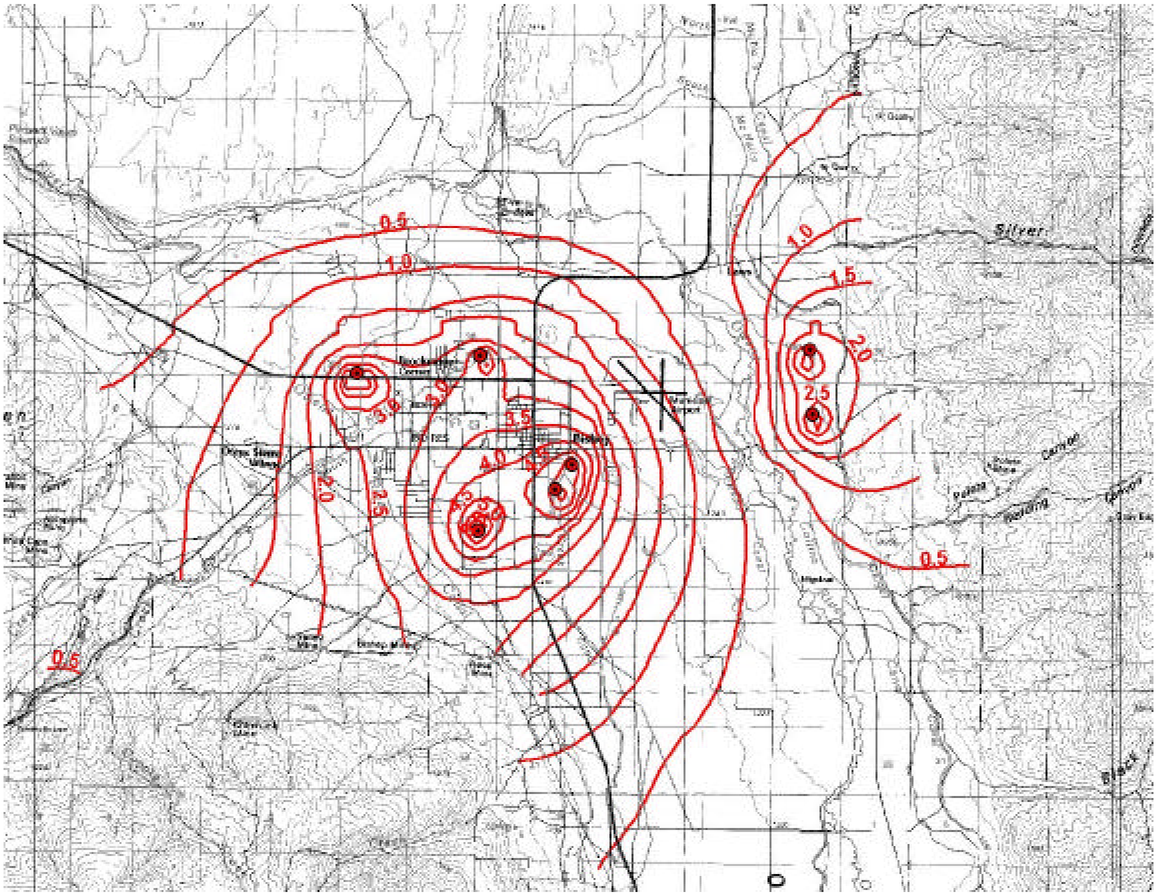

Figure 18. Drawdown due to operation of new production wells identified in FEIR (1991). Contour interval is 0.5 m.

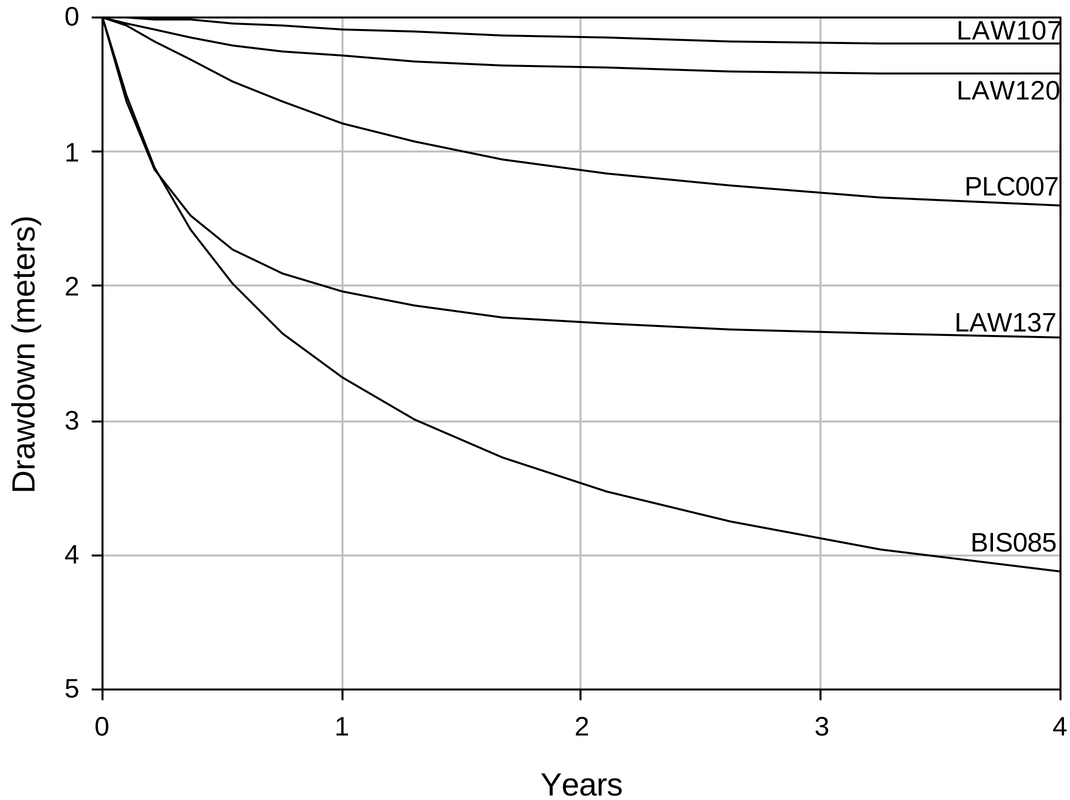

Figure 19. Drawdown at groundwater dependent vegetation parcels due to operation of new production wells identified in FEIR (1991).

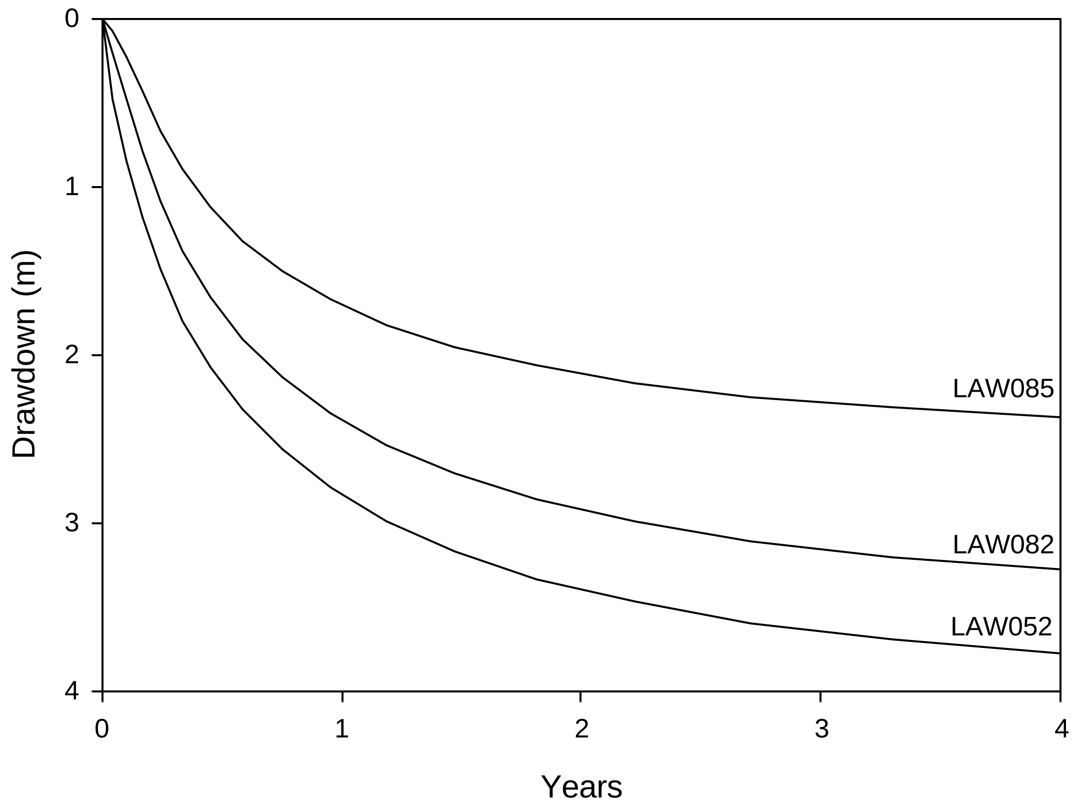

Figure 20. Drawdown beneath three vegetation parcels in Laws due to discontinuation of flow in the McNally Canals.

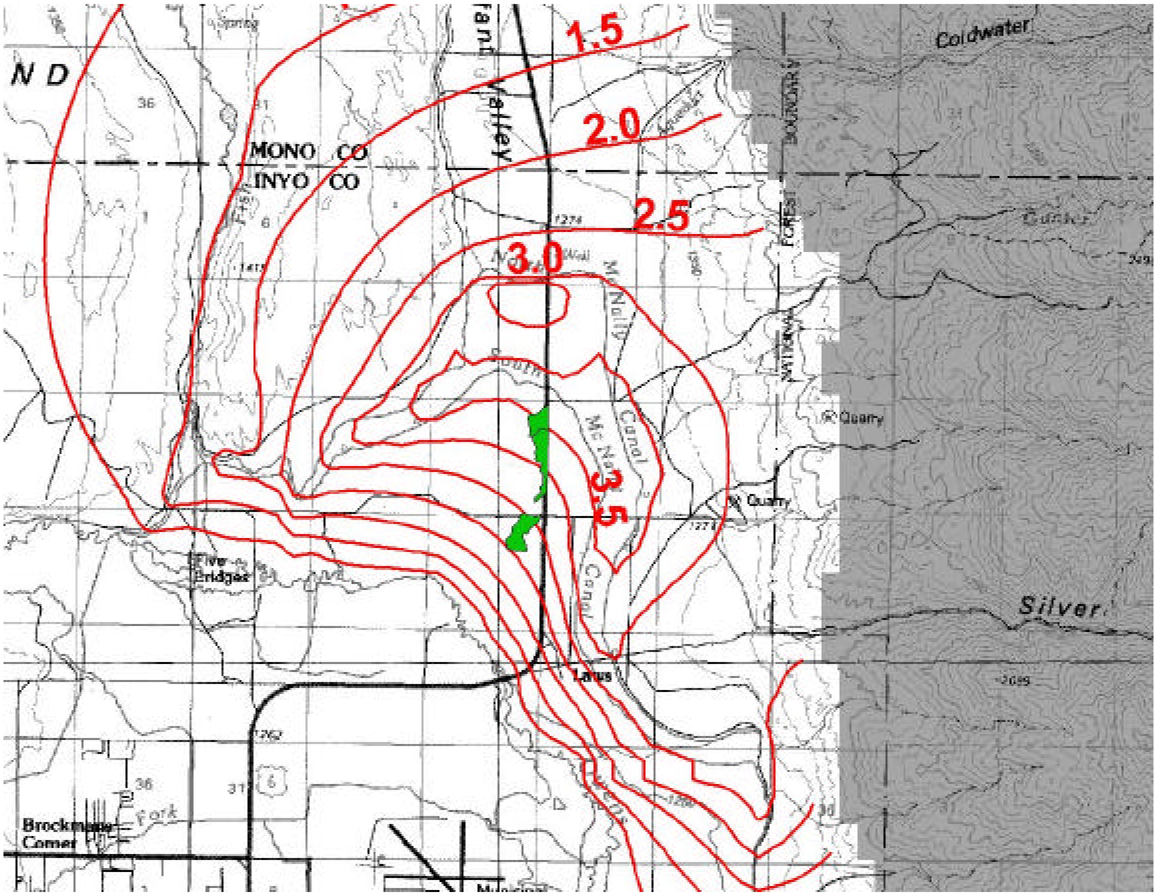

Figure 21. Drawdown due to removal of recharge due to McNally Canals and associated water spreading. Contour interval is 0.5 m. Vegetation parcels shown in Figure 20 are shown in green, north to south: LAW052, LAW082, and LAW085.

APPENDIX 1: Hydraulic head calibration targets.

Well	UTM north.	UTM east.	head (mamsl)	Layer
T012U	379738	4131193	1235.71	1
T02AI	381623	4128527	1222.19	1
T107	379622	4145762	1261.25	1
T108	373332	4137353	1290.43	1
T110A	373733	4140874	1277.51	1
T276A	379198	4147635	1268.65	1
T304A	377363	4137236	1257.63	1
T306B	375733	4137735	1265.70	1
T313A	380593	4143817	1254.20	1
T315A	384033	4128896	1215.68	1
T317A	383500	4130458	1219.10	1
T318A	383676	4131253	1220.34	1
T320A	382596	4132767	1224.60	1
T321A	382408	4133686	1226.71	1
T324A	381445	4135523	1231.59	1
T325A	381155	4136315	1233.02	1
T328A	379364	4148648	1274.14	1
T333A	374039	4135743	1287.16	1
T384	374648	4138944	1271.22	1
T385	374656	4139373	1267.68	2
T386	376418	4132549	1245.35	1
T387	374901	4134488	1277.43	2
T389	374138	4134803	1287.32	1
T390	373291	4135870	1298.08	1
T391	371978	4136716	1310.59	1
T430	376896	4132784	1246.54	1
T433A	379955	4139685	1243.59	1
T434	380353	4139815	1245.02	1
T435	379817	4142023	1252.84	1
T436	379678	4141490	1250.45	1
T438	376921	4142135	1260.70	1
T439	376609	4142128	1260.88	1
T474	384654	4120857	1201.56	1
T476A	380641	4120952	1210.41	1
T478A	381509	4122353	1209.82	1
T479	383217	4123706	1208.41	1
T480	381666	4126799	1218.34	1
T481	382077	4129585	1223.34	1
T485	380504	4131637	1232.94	1
T486	384077	4126769	1210.55	1
T487	384345	4129039	1215.75	1
T488	383806	4132429	1224.07	1
T489	382204	4135619	1231.41	1
T490	382197	4138010	1238.86	1
T491	383069	4138566	1248.71	1

Well	UTM north.	UTM east.	head (mamsl)	Layer
T492	381189	4141486	1251.24	1
T494	380608	4143800	1258.73	1
T496	380661	4139586	1243.85	1
T497	378556	4139703	1251.62	1
T498	377250	4139712	1257.85	1
T500	381213	4134020	1233.48	1
T501	378967	4136619	1244.81	1
T503	380282	4140319	1247.62	1
T512	367555	4139360	1326.03	1
T513	377400	4135711	1256.13	1
T573	382164	4138425	1240.90	1
T574	381196	4139035	1243.33	1
T575	380610	4139943	1245.98	1
T576	377415	4141586	1257.38	1
T577	379868	4143373	1258.12	1
T578	379573	4144553	1260.89	1
T580	380604	4140718	1248.44	1
T605	379694	4143876	1259.38	1
T606	379656	4143893	1259.10	1
T624	382273	4138884	1245.93	2
T625	382326	4138742	1245.44	2
T698	380812	4145651	1260.53	1
T699	380630	4144920	1261.01	1
T701	381618	4143691	1257.20	1
T702	379539	4142995	1257.27	1
T704	375934	4141838	1263.06	1
T705	379806	4141883	1252.27	1
T706	380992	4140256	1248.23	1
T707	382065	4139321	1249.75	1
T708	382241	4138889	1249.88	1
T713	385897	4120880	1200.67	1
T734	381502	4144282	1257.57	2
T735	381628	4143696	1255.88	2
T746	373906	4141334	1274.82	1
T748	364902	4140252	1329.55	1
T749	364902	4140252	1329.15	1
T750	364902	4140252	1329.49	1
T751	364902	4140252	1335.07	1
T753	373041	4141848	1279.91	2
T756	375559	4141006	1263.84	1
T757	375559	4141006	1264.84	3
T758	375559	4141006	1265.60	3
T759	375559	4141006	1263.87	2
T795	378979	4143207	1259.20	1
T796	383668	4132145	1222.79	1
T797	379141	4127075	1227.30	1
T825	375876	4141583	1263.57	1

Well	UTM north.	UTM east.	head (mamsl)	Layer
T826	375848	4141440	1263.06	1
T827	375822	4141339	1263.25	1
T828	375788	4141206	1263.41	1
T829	375759	4141082	1263.07	1
T830	375438	4141257	1265.02	1
T831	374338	4140800	1271.70	1
T835	380458	4142785	1255.75	1
T836	379240	4141829	1251.59	1
T837	377880	4141193	1253.58	1
T838	376535	4140851	1259.85	1
T839	381670	4139561	1250.19	1
T840	381187	4139124	1244.07	1
T841	383332	4137245	1243.47	1
T842	383368	4124928	1209.01	1
V001G	380515	4141987	1252.50	1
V135	379492	4137857	1244.77	2
V137	374451	4134906	1284.11	1
V145	378610	4129584	1235.21	2
V149	373548	4136853	1288.59	2
V201	377348	4135707	1256.61	2
V208	376756	4137785	1257.67	2
V234	375731	4138667	1265.90	1
V242	382972	4138937	1249.12	3
V250	381162	4139757	1247.46	2
V252	380706	4146062	1260.64	1
V253	380814	4145668	1260.66	2
V261	379313	4152092	1282.90	1
V262	380822	4144950	1260.52	1
V265	380706	4146855	1261.34	1
V269	379699	4143827	1258.84	1
V270	381435	4143604	1258.80	1
V275	380626	4144905	1260.87	1
V277	368090	4137209	1340.10	2
V279	371937	4137376	1301.51	1
V281	369958	4138317	1323.92	1
V284	380808	4150887	1284.22	1
V286	381306	4144093	1258.54	1
V287	378932	4125854	1228.42	1
V288	382345	4139334	1249.22	1
V289	378460	4143919	1258.45	1
V290	379542	4142982	1256.73	1
V292	378106	4132584	1244.91	3

APPNEDIX 2: Model files.

Provided on compact disc are the model files produced by this study. Three sets of model files are provided: the directory 'steady-state' contains the files for the calibrated steady-state model; the directories 'eir_wells' and 'no_macs' provide the files for the two predictive simulations. Each directory contains MODFLOW-96 input and output files (Harbaugh and McDonald, 1988), and Groundwater Vistas interface files. Groundwater Vistas is not required to run the MODFLOW files; they are standard MODFLOW-96 formats that can be read by MODFLOW-96.