Hydrogeology, Hydrologic Effects of Development, and Simulation of Groundwater Flow in the Borrego Valley, San Diego County, California

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Executive Summary

The Borrego Valley is a small valley (110 square miles) in the northeastern part of San Diego County, California. Although the valley is about 60 miles northeast of city of San Diego, it is separated from the Pacific Ocean coast by the mountains to the west and is mostly within the boundaries of Anza-Borrego Desert State Park. From the time the basin was first settled, groundwater has been the only source of water to the valley. Groundwater is used for agricultural, recreational, and municipal purposes. Over time, groundwater withdrawal through pumping has exceeded the amount of water that has been replenished, causing groundwater-level declines of more than 100 feet in some parts of the basin. Continued pumping has resulted in an increase in pumping lifts, reduced well efficiency, dry wells, changes in water quality, and loss of natural groundwater discharge. As a result, the U.S. Geological Survey began a cooperative study of the Borrego Valley with the Borrego Water District (BWD) in 2009. The purpose of the study was to develop a greater understanding of the hydrogeology of the Borrego Valley Groundwater Basin (BVGB) and to provide tools to help evaluate the potential hydrologic effects of future development. The objectives of the study were to (1) improve the understanding of groundwater conditions and land subsidence, (2) incorporate this improved understanding into a model that would assist in the management of the groundwater resources in the Borrego Valley, and (3) use this model to test several management scenarios. This model provides the capability for the BWD and regional stakeholders to quantify the relative benefits of various options for increasing groundwater storage. The study focuses on the period 1945–2010, with scenarios 50 years into the future.

This report documents and presents (1) an analysis of the conceptual model, (2) a description of the hydrologic features, (3) a compilation and analysis of water-quality data, (4) the measurement and analysis of land subsidence by using geophysical and remote sensing techniques, (5) the development and calibration of a two-dimensional borehole-groundwater-flow model to estimate aquifer hydraulic conductivities, (6) the development and calibration of a three-dimensional (3-D) integrated hydrologic flow model, (7) a water-availability analysis with respect to current climate variability and land use, and (8) potential future management scenarios. The integrated hydrologic model, referred to here as the "Borrego Valley Hydrologic Model" (BVHM), is a tool that can provide results with the accuracy needed for making water-management decisions, although potential future refinements and enhancements could further improve the level of spatial and temporal resolution and model accuracy. Because the model incorporates time-varying inflows and outflows, this tool can be used to evaluate the effects of temporal changes in recharge and pumping and to compare the relative effects of different water-management scenarios on the aquifer system. Overall, the development of the hydrogeologic and hydrologic models, data networks, and hydrologic analysis provides a basis for assessing surface and groundwater availability and potential water-resource management guidelines.

The groundwater-flow system consists of three aquifers within the BVGB: upper, middle, and lower. The three aquifers—which were identified on the basis of the hydrologic properties, age, and depth of the unconsolidated deposits—consist of gravel, sand, silt, and clay alluvial deposits and clay and silty-clay lacustrine deposits. Recharge is primarily the infiltration of runoff from the surrounding mountains. Infiltration of return flows from agricultural irrigation is an additional source of recharge to the aquifer system. Some underflow from the surrounding tributary basins also contributes to recharge of the BVGB. Partial barriers to horizontal groundwater flow, such as faults, have been identified on the eastern edge of BVGB. Prior to groundwater development in the BVGB, groundwater flowed from the recharge areas, generally near the margins of the basin, to discharge areas around the Borrego Sink, where it discharged from the aquifer system through evapotranspiration. Groundwater-level declines owing to groundwater development have eliminated the natural sources of discharge, and pumping for agricultural, recreational, and municipal uses has become the primary form of discharge from the groundwater system.

The quality of groundwater in the Borrego Valley is a concern because of reliance on groundwater for agricultural, recreational, and municipal supply. Groundwater quality can be affected by land-use activities occurring at or near land surface. These activities include irrigation of vegetated landscapes and the use of septic systems to dispose of wastewater. Groundwater quality can also be affected by declining groundwater levels, because there is the potential for a change in the distribution of flow from underlying aquifers to wells. Historical and current groundwater-quality data were used to determine which constituents were present in relatively high concentrations compared to State water-quality thresholds and whether these constituent concentrations had changed in response to declining groundwater levels. Age-dating isotopes (tritium and carbon-14 [^{14}C]) were analyzed to determine whether modern (tritium-containing) groundwater recharge is occurring in Borrego Valley. Major findings of the groundwater-quality part of this study follow.

- Historical water-quality data show that, in the upper aquifer, total dissolved solids (TDS) and nitrate (as N) exceeded their water-quality thresholds of 500 mg/L (secondary recommended California maximum contaminant level) and 10 mg/L, respectively. At the time of publication, the source of this nitrate is unknown.

- TDS and sulfate are the only constituents that show increasing concentrations with simultaneous declines in groundwater levels.

- TDS and nitrate concentrations were generally highest in the upper aquifer and in the northern part of the Borrego Valley where agricultural activities are primarily concentrated.

- Age-dating isotopes indicate that little natural groundwater recharge is occurring under current (1900–2000) climatic conditions and that almost all of the natural recharge is occurring adjacent to the mountain fronts.

The long-term extraction of groundwater causes increases in the effective or intergranular stresses in the aquifer-system materials; this increased stress can result in irreversible compaction of the aquifer system. This compaction results in land subsidence in many areas where long-term pumping, typically in excess of recharge, has depleted groundwater storage. Three methods were employed as part of this study to assess the land subsidence in Borrego Valley: Global Positioning System (GPS) surveys, continuous GPS (CGPS) data collection, and interferometric synthetic aperture radar (InSAR) remote sensing techniques. InSAR results, derived from synthetic-aperture radar data, provide spatially detailed ground deformation maps (interferograms) that can elucidate spatially detailed patterns of vertical deformation for specific time spans. The InSAR methods complement the GPS surveys and CGPS data, which provide time-series data at a series of points. The GPS surveys, CGPS data, and InSAR analyses show little land subsidence has occurred in the Borrego Valley (much less than 1 inch in the last 50 years, 1961–2010). Hence, land subsidence attributed to aquifer-system compaction is not currently a problem in the Borrego Valley and is unlikely to be a significant problem in the future.

The GPS surveys were also used to improve the previous crude determinations of elevations for groundwater wells, which were derived from topographic maps and from which groundwater levels and groundwater-level gradients were determined. Historical land-surface elevations were updated for 79 groundwater wells. Historical elevations were changed by more than 5 feet at 10 wells and by almost 30 feet at 1 well. The updated elevations give a better estimate of spatially distributed groundwater levels, particularly the locations of highs and lows of the groundwater table.

The BVHM was developed on the basis of historical conditions (66 years) for the analysis of the use and movement of groundwater and surface water throughout the valley and to provide a basis for addressing groundwater availability and sustainability analyses. The model has a uniform horizontal discretization of 92 acres per cell (2,000 ft by 2,000 ft) and is oriented subparallel to the tectonic structure and to Coyote Creek. Vertically, the model has three layers representing the upper, middle, and lower aquifers. The model was calibrated by using groundwater-level measurements for 1945–2010 and simulates conditions during that period. Natural and anthropogenic recharge and discharge, and the transient nature of these stresses, were simulated.

The main sources of recharge to the system are runoff from creeks and streams draining the surrounding watershed, which quickly seeps into the permeable streambeds and infiltrates through the unsaturated zone, and groundwater underflow from the adjacent basins. Exceptionally large and infrequent storms typically contribute the most water to recharge. Excess flow sometimes terminates in middle of the valley at the Borrego Sink or flows out the southeastern end of the valley along San Felipe Wash. Over the 66-year study period, on average, the natural recharge that reached the saturated groundwater system was approximately 5,700 acre-feet per year (acre-ft/yr), but natural recharge fluctuated in the arid climate from less than 1,000 to more than 25,000 acre-ft/yr. On average, of the 5,700 acre-ft/yr, about 1,700 acre-ft/yr seeps into the ground during wet years and rapidly discharges as evapotranspiration. In addition, approximately 1,400 acre-ft/yr enters the basin as underflow from adjacent basins. Since agricultural, recreational, and municipal land uses have been developed, a relatively small amount of recharge also occurs from excess irrigation water and septic-tank effluent. Recharge from irrigation return flows, as indicated by the model results, was about 10–30 percent of agricultural and recreational pumpages. Although a small amount of recharge from septic systems occurs and can be important locally, it is negligible relative to natural recharge and return flow from agricultural and recreational pumpages.

The BVHM uses a one-dimensional unsaturated-zone model to estimate the delay associated with return flow moving through the unsaturated zone. Depending on the thickness, permeability, and residual moisture content in the relatively thick unsaturated zone, it takes tens to hundreds of years for the bulk of return flow to reach the water table. In addition, not all water that reaches the root zone reaches the water table because some water is lost through evapotranspiration or goes into storage in the unsaturated zone. Therefore, in many areas, water that is applied to previously unirrigated land arrives at the underlying water table decades or longer after it is applied.

Groundwater discharge occurs in three primary forms: (1) evapotranspiration from the ground and through the direct uptake of plants (mostly in and around the Borrego Sink); (2) a small amount of seepage from the southern end of the basin; and (3) groundwater pumping for agricultural, recreational, and municipal uses. Natural discharge from evapotranspiration ranges from approximately 6,500 acre-ft/yr prior to development to virtually zero in the last several decades (1990–2010), because the groundwater levels in the basin dropped below the reach of the mesquite in the basin. Underflow out the southern end of the basin was small and relatively stable over time, at about 500 acre-ft/yr. Groundwater pumpage for agriculture and recreation was estimated on the basis of irrigated acreage and consumptive-use data. Values of pumpage for municipal supply were compiled from water-use records. Estimated combined annual agricultural, recreational, and municipal pumpage peaked at around 19,600 acre-ft from 2005 to 2010.

Results of the calibrated model simulations indicated that simulated groundwater pumpage exceeded simulated actual natural recharge in most years, resulting in an estimated cumulative depletion of groundwater storage of about 450,000 acre-ft from 1945 to 2010. Groundwater pumping resulted in simulated groundwater-level declines of more than 150 ft from 1945 conditions in much of the northern portion of the study area. The decline in groundwater levels was the result of this depletion of groundwater storage. In turn, the simulated decline in groundwater levels resulted in the elimination of almost all of natural discharge through evapotranspiration from the groundwater basin. Because there are few fine-grained, compressible deposits in the aquifer system materials, little aquifer-system compaction and land subsidence have occurred.

The calibrated BVHM was used to simulate the response of the aquifer system to six future 50-year (2011 to 2060) pumping scenarios: (1) no change in the agricultural, recreational, and municipal pumpage rates (status quo); (2–4) various levels of reductions in agricultural and recreational pumpage rates, coupled with low to high increases in municipal pumping rates; (5) reduction of all groundwater pumpage to that needed to avoid future groundwater-storage depletion over 50 years; and (6) a less severe, but more rapid, reduction in all groundwater usage over 20 years, followed by 30 years at a constant much lower pumpage rate.

Results from Scenario 1 (continuation of current, 2010, annual pumpage) indicated that the drawdown observed since pre-development would continue, with a total depletion in groundwater storage of about 1,000,000 acre-ft by 2060. Consequently, the water table declines to the middle aquifer in some areas. Because of the lower hydraulic conductivity and storage properties of the middle aquifer relative to the upper aquifer, continued pumping at these rates would result in larger, more rapid groundwater-level declines in the future and possibly a reduction in groundwater quality. As a result, more or deeper wells could be needed to accomplish similar pumpage rates. Scenarios 2–4 represent combinations of changes in agricultural and recreational pumpages, as well as in municipal pumpage. Although less than Scenario 1 (status quo) pumpage rates, pumpage rates in two of these three scenarios exceed the average annual recharge rate, groundwater levels continue to decline, and there is continued cumulative depletion of groundwater storage. Because more water is being extracted from the groundwater basin than is being recharged either through natural or induced means, groundwater levels continue to decline. As the groundwater table is lowered from the relatively storage-rich and permeable upper aquifer to the middle and lower aquifers, the rate and areal extent at which groundwater levels decline accelerate, and the areal extent over which storage changes would be affected would be larger in the middle and lower aquifers with lower storativities. Furthermore, if the groundwater quality is less desirable deeper in the system, as existing information indicates, then the water quality of groundwater pumpage would deteriorate as deeper sources of water contribute more water to supply wells; this water could require more advanced water treatment than is used at present (2010) for municipal, and potentially, irrigation supply.

The location of the largest drawdown varies with the relative contributions of the three water-use categories (agricultural, recreational, and municipal) to overall pumpage in each scenario. In Scenario 5, water use is reduced in all three categories (agricultural, recreational, and municipal) to reach a sustainable level over a 50-year time span. The California Sustainable Groundwater Management Act (SGMA) of 2014 requires basins to reach sustainable yield. Scenario 5, with its 50-year time span, covers a longer period than is required by the act. The sustainable level for the Borrego Valley, assuming no significant degradation in groundwater quality, equates to total discharge equaling the long-term average recharge to the basin. As human activities change the system, the components of the water budget (inflows, outflows, and changes in storage) also change and must be accounted for in any management decision. Because there currently is little effect on captured recharge or discharge, in this system, 'sustainability' is a maximum amount of discharge to avoid future groundwater-storage depletion and is being simplified and equated to this average recharge. As the rate of total groundwater extraction approaches the rate of recharge (meaning all inflows—natural and anthropogenic recharge, including induced recharge from captured water sources) to the aquifer system, the change in groundwater storage, and thus the rate of groundwater storage depletion, approaches zero, indicating no additional loss in storage. In the long run, the average change in groundwater storage would be negligible when the basin is operated at the sustainable level; however, groundwater levels and storage changes would fluctuate as they have historically with climatic variability. For example, during relatively wet years, more water could go into storage than is extracted. In turn, during moderate and relatively dry years, more water would be extracted than goes into storage.

In order to simulate a realistic approach for meeting SGMA requirements on the 20-year SGMA timeline for implementation, in Scenario 6, municipal and recreational pumpages both were reduced to 50 percent of current (2010) rates, and agricultural pumpage was reduced to 40 percent of current rates. These reductions were applied linearly over 20 years and continued for the next 30 years until 2060. With these reductions, at 2060, recharge approximates discharge. Simulated drawdowns are approximately 50 feet over a broad part of the basin. Drawdown and groundwater-storage losses continue in areas where agricultural, recreational, and municipal pumping occurs. In the long run, groundwater levels would stabilize and would not decline as they would for the Scenario 1 simulation, which had continued significant groundwater level and storage declines. However, changes in groundwater storage would fluctuate with climatic variability. Because climate models indicated greater variability in natural recharge in the future than during historical periods, the variability of groundwater-storage changes could also increase. Managed artificial recharge through engineered, enhanced infiltration of storm water or imported surface water is a water-management strategy that could help alleviate the demands on the valley's groundwater system.

Introduction

The Borrego Valley is a small valley in the northeastern part of San Diego County, California, about 60 miles northeast of San Diego (fig. 1). Native Americans inhabited the valley and utilized the springs and surface-water sources from the nearby mountain ranges. Cattlemen began homesteading the Borrego Valley in about 1875. The first successful modern well was dug in 1926, which quickly led to irrigation farming (Moyle, 1982). By then, the valley's population center, the small desert community of Borrego Springs, included a post office, a small general store, and a gas station. Historically, the principal source of water for the valley has been groundwater. The Anza-Borrego Desert State Park, which has 600,000 acres in and around the Borrego Valley, was established in 1933 (fig. 1). The park was established to protect this unique desert environment. The military presence both of the Army and Navy during World War II brought the first paved roads and electricity to Borrego Springs. After the war, land developers subdivided the area, attempting to create a resort community supported by an increase in tourism generated by the Anza-Borrego Desert State Park (fig. 1).

The residents of the valley rely on groundwater for drinking water and irrigation (Moyle, 1982; Mitten and others, 1988; California Department of Water Resources, 2003). Irrigated agriculture, golf courses, residential and commercial uses, and the Anza-Borrego Desert State Park require five times more water than is available through natural recharge. The imbalance between recharge and discharge, which began in the mid-1940s, has caused long-term groundwater-level declines. Moyle (1982) estimated that from 1945 to 1980 about 330,000 acre-feet (acre-ft) of groundwater was pumped from the basin in excess of recharge. As a result, by 2010, the northern part of the groundwater basin had groundwater-level declines of about 120 feet (ft; fig. 2). Therefore, the U.S. Geological Survey (USGS), in cooperation with the Borrego Water District (BWD), undertook this water-resource assessment to understand the hydrologic budget and the limits of groundwater availability better in order to avoid future groundwater-storage depletion. The purpose of the study was to develop a greater understanding of the hydrogeology of the Borrego Valley Groundwater Basin (BVGB) and provide tools to evaluate the potential hydrologic effects of future development. The objectives of the study were to (1) improve the understanding of groundwater conditions and land subsidence, (2) incorporate this improved understanding in an integrated hydrologic model to aid in managing the groundwater resources in the Borrego Valley, and (3) apply this model to test several management scenarios. An integrated hydrologic model can provide the capability for the BWD and regional stakeholders to quantify the relative benefits of various options for reducing groundwater overdraft.

The California Sustainable Groundwater Management Act (SGMA) requires that groundwater basins reach sustainable yield. SGMA sets a 20-year timeline for implementation. Overdrafted basins must achieve groundwater sustainability by 2040 or 2042, predicated on the implementation of plans, which are expected to take 5 to 7 years to complete. The SGMA recognizes that groundwater is managed at the local or regional level best and that there are geographic, geologic, and hydrologic differences accounting for groundwater supply. The goal of this legislation is reliable groundwater management, which it defines as "the management and use of groundwater in a manner that can be maintained during the 5-to-7-year planning period and 20-year implementation horizon without causing undesirable results" (California Department of Water Resources, 2015). Undesirable results are defined as any of the following effects:

The BVHM was developed on the basis of historical conditions for the analysis of the use and movement of water throughout the valley to provide a basis for addressing groundwater availability and sustainability analyses. The BVHM was constructed in three major phases. The first phase was the conversion of the existing flow models into an updated OWHM model. In the second phase, new and existing data were collected, compiled, and combined. In this step, the hydrogeologic framework model was developed from the previous studies and new data. This framework model includes stratigraphic units and the distribution of hydraulic properties. In the final step, the inflows and outflows of the updated and revised conceptual model were combined with the hydrogeologic framework model into the BVHM. The components (processes and packages) of OWHM used for the BVHM are summarized in table 9.

The BVHM was adjusted during implementation of these model development phases, but calibrated primarily after the final phase both by using trial-and-error and automated parameter-estimation methods. The automated nonlinear regression-based parameter-estimation software, referred to as PEST (Doherty, 2010a, b, c; Doherty and Hunt, 2010), was used to help with the calculation of sensitivities and parameter estimation. The model was calibrated to groundwater levels and groundwater level differences (drawdown).

The Borrego Valley was split into three major water-balance regions on the basis of water-use types (agricultural usage; recreational usage; and other usage, including undeveloped native and historical phreatophytic, residential, and municipal areas) for water accounting purposes. These three regions comprise 52 water-balance subregions (WBSs) that roughly coincide with the current major parcels in the valley (table 10). For ease of description, even though land use varied over time within these subregions, the subregion boundaries were kept constant over time.

The BVHM model components can be grouped in terms of the discretization and boundaries, initial conditions, aquifer characteristics, simulation of recharge, water-balance subregions, land use, simulation of discharge, and groundwater inflows and outflow. The next few sections summarize the model components within these groups.

Discretization and Boundaries

The BVHM includes the major alluvial deposits of the entire Borrego Valley, bounded on the northeast and east by the Coyote Creek fault, on the south by the Vallecito Mountains, and on the west and northwest by the San Ysidro Mountains (fig. 33). The southeastern boundary coincides with the surface-water divide, which is southwest of Ocotillo Wells and represented by constant-head boundary cells in the BVHM (fig. 33). The finite-difference model grid used to represent the land surface and the subsurface alluvial deposits consists of a series of orthogonal square model cells (fig. 33).

Spatial Discretization

The total active modeled area is 73,876 acres on a finite-difference grid consisting of 30 rows, 75 columns (2,250 cells), and 3 layers (fig. 33). About 36 percent of the cells (803 cells) are an active part of the hydrologic model. The model grid has a uniform horizontal discretization of about 92 acres per square cell (2,000 ft by 2,000 ft) and is oriented subparallel to the tectonic structure and Coyote Creek 22 degrees west of true north (fig. 33). The grid orientation and cell size were chosen to be parallel to the general direction of groundwater flow and the same as previous models to facilitate the upgrade from existing models. The coordinates for the total model grid are summarized in table 11.

The model layering is a series of three layers that are aligned with the aquifers discussed previously. The top of the hydrologic model is represented by the elevation of the land surface and is a composite of model layers 1 and 3 (fig. 33). The upper aquifer model layer (layer 1) ranges in thickness from an assumed minimum of 50 ft to an estimated maximum of about 643 ft. The second model layer is coincident with the middle aquifer and ranges in thickness from an assumed minimum of 50 ft to an estimated maximum of about 908 ft. The third model layer is coincident with the extent of the lower aquifer and ranges in thickness from an assumed minimum of 50 ft to an estimated maximum of about 3,831 ft.

Temporal Discretization

In order to represent the growing season adequately, and the dynamics of changing precipitation, streamflow, and PET that collectively drive the major water supply and demand components, the annual hydrologic cycle of the BVHM was discretized into monthly stress periods and two equal time steps per stress period. Periods of user-specified model inflows, outflows, and boundary heads are referred to as stress periods. Variations in stresses are simulated by changing these model inputs from one stress period to the next. The inputs, which include groundwater pumping, precipitation, PET, stream inflows, water applied to irrigate crops, and underflow beneath the major streams, are assumed to be constant within each stress period. Stress periods are further divided into two time steps per stress period (month), which are units of time for which groundwater levels and flows are numerically simulated for all model cells. The total simulation period was 60.25 years (or 975 monthly stress periods) from October 1929 through December 2010. The first 192 stress periods (years 1930–45) are considered a model spin-up period, and the model calibration as well as the target simulation period used for analysis was October 1945 through December 2010.

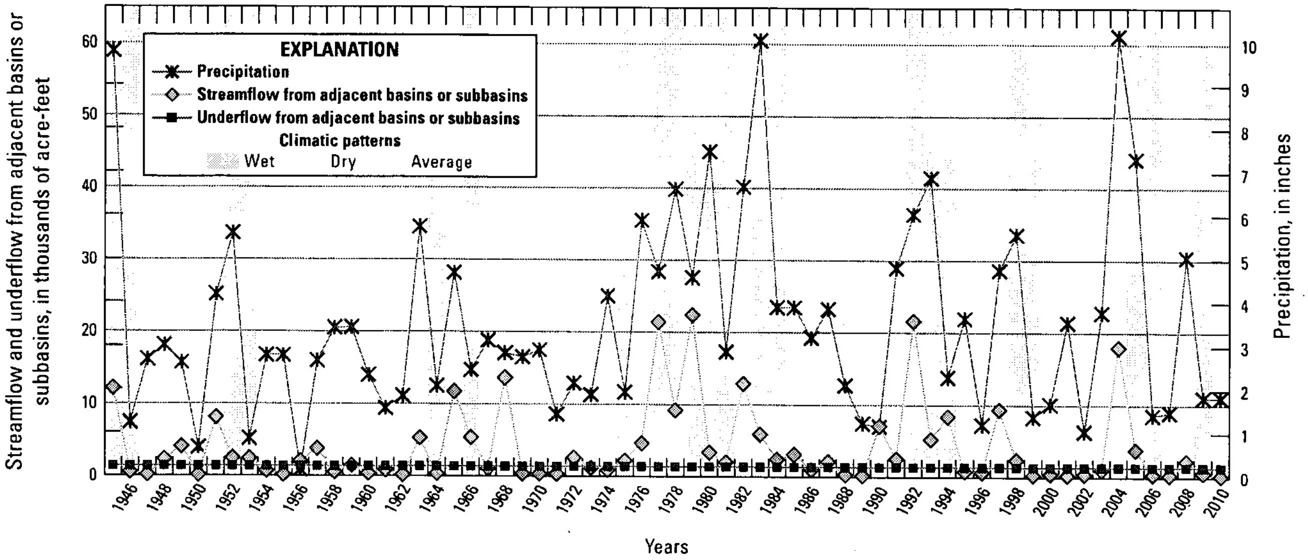

Figure 49. Precipitation, streamflow, and underflow from adjacent watersheds and basins for the Borrego Valley, California, 1945–2010.

The simulated landscape budget is shown in figure 50. As in the previous figures, the graph in figure 50*A* uses the climatic pattern for the 66-year simulation period and the estimated land-use pattern from pre-development through 2010. The magnitude of precipitation that is directly evaporated as a result of the arid conditions in the valley is shown in figures 50*A* and *B*. As a result, little unsaturated-zone recharge occurs from direct precipitation. Figures 47*A*, 48*A*, and 50*A* and table 19 show that despite the variability in climate, ET from groundwater was relatively constant before development at about 7,100 acre-ft/yr. The ET from groundwater both enters and leaves the landscape system and directly links the landscape process with the groundwater-flow process (fig. 50). Figures 47*B* and 50*B* show that pumpage totals around 19,000 acre-ft/yr in recent years (2005–10). In the budgets, groundwater pumpage is balanced by reductions of ET from groundwater and groundwater storage (figs. 47*B*, 48*B*, 50*B*).

The simulated monthly groundwater budget components during 2010 are shown in figure 51. As expected, the pumpage (and groundwater-storage loss) increases during the warmer summer months and decreases during the winter and early spring. January and October show some small decreases relative to the adjacent months, most likely reflecting local variability. Recharge from streamflow from the upstream portion of the watershed does not vary dramatically because 2010 was a comparatively dry year; because underflow was specified in the model by use of a head-dependent flow boundary, and heads near this boundary are largely unaffected, underflow is approximately equal to the predevelopment rate. Recharge through the unsaturated zone increases slightly during the winter and early spring. The ET from groundwater appears to increase slightly in the spring, when groundwater levels are higher from stormflow, and phreatophytic vegetation would be most active. The small amount of discharge out the southern end through the constant-head boundary is largely unaffected, and flow out of the system is approximately equal to the predevelopment rate.

Table 19. Simplified groundwater budget for pre-development and 2010, Borrego Valley Hydrologic Model, Borrego Valley, California.

[na, not applicable]

Groundwater budget (acre-feet per year)	Pre-development (average)[1]	2010
IN		
Unsaturated-zone recharge	1,719	1,225
Streamflow and underflow from adjacent watersheds	5,395	1,587
Storage loss	478	15,568
OUT		
Flow out southeastern end (constant head)	518	517
Evapotranspiration of groundwater	7,074	453
Pumpage	na	17,410

[1] Average based on climatic conditions without development for 1945 through 2010.

The simulated annual changes in storage and the cumulative change (loss) in storage, given the climatic variability from 1945 through 2010, are shown in figure 52. Because the period from 1945 through 1970 was generally dry, there is a cumulative loss in storage from natural sources. This loss is recovered during the relatively wetter period from 1971 to 2010 (fig. 52). The magnitude of these changes is small, however, compared to the magnitude of storage change resulting from groundwater development (fig. 52). Because discharge (groundwater pumping) has exceeded recharge for most of the 66-year simulation period, and no other sources of inflow to the groundwater system are available for capture, a significant amount of water has been removed from storage. For the simulation period, approximately 440,000 acre-ft of water were removed from storage in the groundwater basin, and nearly 400,000 acre-ft can be attributed to pumpage.

Future Groundwater-Management Scenarios

The simulation results in the previous section, along with the measured changes in groundwater levels, indicate that groundwater usage currently exceeds the amount of water recharging the Borrego Valley. As a result, groundwater is being removed from storage, and water availability is likely to be a limiting factor in meeting future water demands. In order to understand the effects of this reduction in storage better, water managers are considering different groundwater management scenarios to manage their available water resources. For this analysis, six water-use scenarios were considered during a 50-year period (2011–60):

1. No change in the magnitude and distribution of pumping, or the 2010 status quo.
2. Low growth over 50 years (agricultural and recreational pumpages are decreased linearly over time to 5 times the 2010 rates for 2060, while municipal pumpage is increased linearly over time to 76 times the 2010 rates for 2060).
3. Medium growth over 50 years (agricultural pumpage is decreased linearly over time to 25 times the 2010 rates for 2060, and recreational pumpage is decreased linearly over time by 50 times the 2010 rates for 2060, while municipal pumpage is increased linearly over time to 33 times the 2010 rates for 2060).
4. High growth over 50 years (agricultural pumpage is decreased linearly over time to zero for 2060, and recreational pumpage is decreased linearly over time by 5 times the 2010 rates for 2060, while municipal pumpage is increased linearly over time to 79 times the 2010 rates for 2060).
5. Water-usage reduction to avoid future groundwater-storage depletion over 50 years (agricultural and recreational pumpage is decreased linearly over time to 32 times the 2010 rates for 2060, and municipal pumpage is decreased linearly over time by 52 times the 2010 rates for 2060).
6. Management scenario water-usage reduction over 20 years (agricultural pumpage is reduced linearly over time to 40 times the 2010 rates for 2030, and recreational and municipal pumpages are each reduced linearly over time to 50 times the 2010 rates for 2030; then, usage is held constant at the 2030 rate for the next 30 years, 2031–60).

The calibrated BVHM was used to simulate the hydrologic effects of the six groundwater management scenarios with monthly stress periods. The projected pumpage rates for the six management scenarios are summarized in table 20. In order to include climate variability in all six of these scenarios, it was assumed that the climatic inputs of the last 50 years repeated in reverse from the last calibration year (2010). Note that this results in a relatively dry period near the end of the simulation. For the first five scenarios, the changes in groundwater pumpage are spread throughout the basin for each of the water-use types (agricultural, recreational, and municipal) evenly over the 50-year scenario simulation. In Scenario 6, the changes occur in the first 20 years, then the land use and municipal pumpage are held constant for the remaining 30 years. Slight variations occur in all scenarios for the agricultural and recreational pumpages owing to climatic factors. For the municipal and Rams Hill recreational pumpage, the pumpage change was accomplished by using a multiplier to change the total pumpage. For agricultural and the remaining recreational pumpage, the reduction was accomplished by randomly removing crops, as needed, for each of the scenario simulations. The cumulative change in groundwater storage for the six water-management scenarios is shown in figure 53. The water tables simulated for each scenario in 2060 are shown along a longitudinal cross section of the basin in figure 54.

Table 20. Groundwater budgets for six management scenarios from the Borrego Valley Hydrologic Model, Borrego Valley, California, 2011–60.

[Pumping rates are in acre-feet per year.]

Scenario	2010 Pumping rates				Percent of 2010 pumping rates			2060 Pumping rates			
	Agricultural	Recreational	Municipal	Total	Agricultural	Recreational	Municipal	Agricultural	Recreational	Municipal	Total
1	13,162	4,113	1,006	18,281	100	100	100	13,162	4,113	1,006	18,281
2	13,162	4,113	1,006	18,281	50	50	176	6,581	2,056	1,771	10,408
3	13,162	4,113	1,006	18,281	25	50	233	3,291	2,056	2,344	7,691
4	13,162	4,113	1,006	18,281	0	50	379	0	2,056	3,813	5,869
5	13,162	4,113	1,006	18,281	32	32	52	4,212	1,316	523	6,051
6[1]	13,162	4,113	1,006	18,281	40	50	50	5,265	2,056	503	7,824

[1] Scenario 6 represents the scalar change occurring over 20 years between 2010 and 2030.

on average, the natural recharge that reaches to the saturated groundwater system is approximately 5,700 acre-ft/yr, but natural recharge fluctuates in the arid climate from less than 1,000 to more than 25,000 acre-ft/yr. Of this 5,700 acre-ft/yr, about 1,700 acre-ft/yr seeped into the ground during wetter years to undergo rapid evapotranspiration. Another approximately 1,400 acre-ft/yr on average comes as underflow from upstream portions of the watershed. Because agricultural, recreational, and municipal land uses have developed, recharge also occurred from excess irrigation and septic-tank effluent. Recharge from irrigation return flows was estimated to be about 20–30 percent of agricultural and recreational pumpages. Although a small amount of recharge from septic tanks occurs, it is negligible relative to natural recharge and return flow from agricultural and recreational pumpages. The BVHM uses a one-dimensional unsaturated-zone model to estimate the delay associated with return flow moving through the unsaturated zone. Depending on the thickness, permeability, and residual moisture content in the relatively thick unsaturated zone, it would take tens to hundreds of years for return flow to pass through the unsaturated zone. In addition, not all water that passes through the root zone reaches the water table because some water contributes to storage in the unsaturated zone as the depth to the water table increases. Therefore, water that is applied to previously unirrigated land might not reach the underlying water table for decades.

Groundwater discharge occurs from three primary sources—(1) evapotranspiration in areas where the water table is shallow and direct uptake from plants (mostly in and around the Borrego Sink) can occur; (2) a small amount of seepage from the southern end of the basin; and (3) groundwater pumpage for agricultural, recreational, and municipal uses. Natural discharge from evapotranspiration ranged from approximately 7,100 acre-ft/yr prior to development to virtually zero during the mid-1990s to 2010, because the groundwater levels in the basin dropped below the reach of the mesquite in the basin. Seepage out the southern end of the basin is small and relatively stable over time, at about 500 acre-ft/yr. Groundwater pumpage for agriculture and recreation was estimated on the basis of irrigated acreage and consumptive-use data. Pumpage for municipal supply was compiled from water-use records. Simulated combined annual agricultural, recreational, and municipal pumpage peaked at around 19,600 acre-ft during 2005–10.

Results of the calibrated model simulations indicate that simulated groundwater pumpage exceeded recharge in most years, resulting in an estimated cumulative depletion in groundwater storage of about 440,000 acre-ft. Groundwater pumping resulted in simulated groundwater levels declining by more than 150 ft relative to 1945 conditions in pumping areas. The decline in groundwater levels is the result of this depletion of groundwater storage. In turn, the simulated decline in groundwater levels has resulted in the decrease in natural discharge from the basin. Because the aquifer system consists of few fine-grained sediments, few areas are susceptible to compaction, and little land subsidence or compaction of fine-grained deposits has occurred.

The calibrated BVHM was used to simulate the response of the aquifer to six future 50-year (2011 to 2060) pumping scenarios: (1) no change in the agricultural, recreational, and municipal pumpage rates, or status quo; (2–4) various levels of reductions in agricultural and recreational pumpage rates coupled with small to large increases in municipal pumpage rates; (5) reduction in all groundwater usage to avoid future groundwater-storage depletion over 50 years; and (6) a less severe, but more rapid, reduction in all groundwater usage over 20 years, followed by 30 years at a constant, much lower usage rate.

Results from Scenario 1 indicate that the total drawdown observed since pre-development would continue, with values exceeding 125 ft in the northern agriculturally dominated part of the valley and groundwater-level declines into the middle aquifer in most of the basin. Because of the lower hydraulic conductivity and storage properties of the middle aquifer relative to the upper aquifer, continued pumping at these rates would result in more rapid water-level declines in the future and possibly a reduction in water quality. Scenarios 2–4 evaluated various combinations of increases and reductions in agricultural, recreational, and municipal pumpages. The pumpage rate in 2 of 3 of these scenarios, although less than in Scenario 1 (status quo), still exceeds the average annual recharge rate. As a result, groundwater levels still decline, and there is a continued cumulative loss in storage. Basically, groundwater levels would continue to drop if more water is being extracted from the groundwater basin than is being recharged on a long-term basis. As more groundwater levels drop from the relatively storage rich and permeable upper aquifer to the middle and lower aquifers, the rate at which groundwater levels would drop and storage depletion would occur would accelerate. Furthermore, if the water quality is less desirable deeper in the system, as existing information indicates, then the water quality of pumped water would deteriorate as well.

In Scenario 5, water usage is reduced in all three categories (agricultural, recreational, and municipal) to reach a sustainable level over a 50-year span. The sustainable level equates to total discharge equaling the long-term average recharge to the basin. In order to avoid future groundwater-storage depletion, agricultural and recreational pumpages were reduced to 32 percent of current rates, and municipal pumpage was reduced to 52 percent of current rates. These changes were applied linearly over 50 years. Simulated maximum groundwater-level declines occurred in the northern and western parts of the basin where pumping is centered. Because agricultural and recreational pumping continues, drawdown and storage losses continue in the areas where this pumping occurs. As the rate of discharge reaches the rate of recharge, there is no net change in storage, and the cumulative loss in storage does not change significantly. Although in the long run, groundwater levels would not rise significantly, and the change in storage would be negligible, in Scenario 5, groundwater levels and storage changes would fluctuate, as they have historically, with climatic variability. For example,