importance in the health of native vegetation requires that precipitation measurements be continued. Additional precipitation measurements near established vegetation study sites (table 1 and fig. 2) will continue to be useful in determining the response of native vegetation to changes in water availability and in understanding the role that other factors play in the health of native vegetation (tables 3 and 5).

**Valleywide evapotranspiration measurements.**—Valleywide measurements of evapotranspiration will aid in detecting changes in native vegetation and in correlating field data with model results. The detailed mapping of native vegetation done by the Los Angeles Department of Water and Power during 1984–88 provides an excellent basis for analysis. However, continued valleywide data collection is needed to aid in evaluating the 1984–88 data set and to detect temporal changes. Remote-sensing techniques may provide a reasonably accurate method of correlating valleywide coverage to site-specific measurements of evapotranspiration and plant density (Jackson, 1985; Reginato and others, 1985).

**Further understanding of native vegetation.**—Continued investigation is needed of the physiology of native vegetation, in particular how water availability and biochemical factors affect plant growth, vegetative stress, and recovery from stress.

### Water Management

**Monitoring of native vegetation near production wells.—**Monitoring of native vegetation, soil moisture, and ground-water levels near production wells and in areas of the valley most susceptible to hydrologic stress (figs. 26, 31, 32, and 33) is needed to aid in making water-management decisions that are based on actual field data.

**Investigation of the ground-water system in the Owens Lake area.**—Future water-management issues, such as rotational ground-water pumpage, probably will involve the Owens Lake area (E.L. Coufal, Los Angeles Department of Water and Water, oral commun., 1992). Prior to additional pumping near the Owens Lake, the area needs to be studied to determine the feasibility of pumping freshwater near a saline lake and the effects of such pumping on native vegetation and on desiccation of the lakebed. The investigation will need to include installation of new wells, logging of lithology and ground-water quality, testing of aquifer characteristics, and monitoring of ground-water levels in different zones of the ground-water system.

**Use of site-specific ground-water flow models.—**Site-specific ground-water flow models, when used in conjunction with information from the valley-wide ground-water flow model, can be extremely useful in efficient testing of hydrologic concepts and possible water-management options. Suggested areas for site-specific models include west of Bishop, near Big Pine, east of Lone Pine, and near Cottonwood Creek. Some site-specific models could take advantage of additional model layers to more accurately represent the hydrogeologic units in the aquifer system.

**Include Round Valley in the water-management analysis.**—As knowledge about the area west of Bishop is improved, it may be advantageous to include Round Valley in future simulations of the Owens Valley ground-water system. Inclusion of Round Valley in the valleywide model will help to confirm underflow rates from Round Valley and the Bishop Tuff and will aid in evaluating any water-management options that include Round Valley.

**More detailed valleywide ground-water flow model.**—Detailed simulations of ground-water flow in complicated areas, such as the Big Pine volcanic and massive lacustrine deposits, may require additional layers in the valleywide model or development of a site-specific model. Updating the valleywide model with improvements in concepts and inevitable changes in recharge and discharge will be necessary at some point after water year 1988 in order to evaluate other water-management alternatives.

## SUMMARY AND CONCLUSIONS

The Owens Valley, a long, narrow valley along the east side of the Sierra Nevada in east-central California, is the main source of water for the city of Los Angeles. The city diverts most of the surface water in the valley into the Owens River–Los Angeles Aqueduct system, which transports the water more than 200 mi south to areas of distribution and use. Additionally, ground water is pumped or flows from wells to supplement the surface-water diversions to the river–aqueduct system. Pumpage from wells used to supplement water export has increased since 1970, when a second aqueduct from the Owens Valley was put into service, and local residents have expressed concerns that the increased pumping may have a detrimental effect on native vegetation consisting of indigenous alkaline scrub and meadow plant communities. This native vegetation on the valley floor depends on soil moisture supplied by precipitation and a relatively shallow water table.

A comprehensive series of studies by Inyo County, the Los Angeles Department of Water and Power, and the USGS was done to determine the effects of ground-water pumping on the survivability of scrub and meadow plant communities and to evaluate alternative methods of water management. Findings from the USGS studies are presented in a series of reports designated Water-Supply Paper 2370 A–H.

This report (Water-Supply Paper 2370-H), as part of that series, integrates findings from the individual studies, which focused on the geology, water resources, and native vegetation of the Owens Valley. This particular study included defining the hydrologic system of the Owens Valley and evaluating the major components of the system and historical changes that have occurred, primarily through use of a valleywide ground-water flow model. The model, which simulates the aquifer system as defined in a companion report by Hollett and others (1991), was calibrated for water years 1963–84 and verified for water years 1985–88. Possible changes in future water management of the Owens Valley, including four general water-management alternatives, were evaluated with the aid of the ground-water flow model.

Major conclusions that resulted from integration of the related studies and from evaluation of the hydrologic system and selected water-management alternatives are summarized below, grouped by general topic.

**Hydrologic System.**—The hydrologic system of the Owens Valley can be conceptualized as having three parts: (1) an unsaturated zone affected by precipitation and evapotranspiration; (2) a surface-water system composed of the Owens River, the Los Angeles Aqueduct, tributary streams, canals, ditches, and ponds; and (3) a saturated ground-water system contained in the valley fill. Since 1913, the hydrologic system in the Owens Valley has been changed substantially by human activities—first by export of large quantities of surface water (virtually the entire flow of the Owens River) via the Los Angeles Aqueduct and later, beginning in 1970, by the additional extraction and export of ground water. Present (1988) water-management practices, which emphasize localized ground-water extractions and artificial recharge, will cause additional, though less extensive changes to the hydrologic system and native vegetation.

**Precipitation, Evapotranspiration, and Native Vegetation.**—Precipitation patterns are influenced primarily by the rain-shadow effects of the Sierra Nevada. As a result, most precipitation from storms falls on the Sierra Nevada; much less falls on the Inyo and the White Mountains farther to the east. As summarized on an equal precipitation map for the Owens Valley drainage area, average precipitation ranges from more than 30 in/yr along the crest of the Sierra Nevada, to less than 6 in/yr on the valley floor, to about 10 in/yr in the White Mountains. A linear relation between altitude and average annual precipitation can be used with measured precipitation at Independence to predict annual precipitation at any location on the valley floor and along the west side of the valley. Although precipitation on the valley floor depends primarily on altitude, precipitation within an individual year can vary widely. Part of this variation is caused by the three different types of storms that move across the valley from different directions and during different times of the year.

Native vegetation covering most of the valley floor depends on soil moisture replenished by both precipitation and the shallow water table. The native vegetation, originally characterized as phreatophytic, has been found to be highly xerophytic and capable of surviving for as much as 2 years or more on soil moisture provided by precipitation. An extended decline in the shallow water table, however, caused by nearby ground-water pumping can cause a substantial loss of leaves and the eventual death of individual plants. These conditions are accentuated during times of drought.

The quantity of evapotranspiration by native vegetation is directly related to the amount of transpiring surface (leaf area) and evaporating surface (bare soil). Less evapotranspiration implies fewer leaves and less total vegetative biomass. Less evapotranspiration, however, does not necessarily imply fewer plants.

By 1984, average annual evapotranspiration from the valley floor was about 35 percent less than prior to 1970. This reduction implies a substantial decrease in transpiration from native plants, and possibly a slight increase in evaporation from bare soil. The reduction in evapotranspiration resulted primarily from increased ground-water pumpage after 1970. Pumping causes a decline of the water table, which reduces replenishment of soil moisture to the overlying unsaturated zone and effectively reduces the quantity of water available to plants for transpiration. Decreases in transpiration and the related decrease in biomass of native vegetation have been greatest close to production wells, but moderate decreases probably have occurred at some distance from the well fields. Changes in the water-table altitude caused by pumping are greatest near the pumped well, but effects of pumping can be communicated over distances of as much as several miles by a slight decrease in ground-water levels. This change in levels (gradient) reduces ground-water flow rates to other parts of the valley as a result of the diversion of ground water to pumped wells.

The infiltration of precipitation to and evapotranspiration from the unsaturated zone are the primary hydrologic processes related to the health of native vegetation. Other biochemical processes probably are important, particularly when water availability is restricted, but knowledge about the effects of such processes on native vegetation in the Owens Valley is meager.

**Surface Water.**—The abundant precipitation that falls, mostly as snow, in the Owens Valley drainage area provides abundant runoff into more than 40 streams that are tributary to the Owens River, the trunk stream of the valley. More than 600 gaging stations are operated by the Los Angeles Department of Water and Power in order to measure runoff into the valley, to allocate water within the valley, and to export water out of the valley to Los Angeles.

The Owens River–Los Angeles Aqueduct system extends from the Mono Basin and the headwaters of the Owens River in the Long Valley, to the outflow point from the Owens Valley at the Haiwee Reservoir and includes several small reservoirs to store and balance flow. More than 100 wells in the Owens Valley pump ground water into the river–aqueduct system to augment flow. Total inflow to the Owens Valley at the Pleasant Valley Reservoir historically has averaged between 250,000 and 330,000 acre-ft/yr, depending on runoff and water-management activities in the Long Valley and the Mono Basin to the north. Export to Los Angeles, which averaged 320,000 acre-ft/yr for water years 1935–69, increased by about 50 percent to an average of 480,000 acre-ft/yr for water years 1970–84.

Annual runoff within the Owens Valley drainage basin ranges from about 50 to 200 percent of the average for water years 1935–84. On the basis of these 50 years of record, a probability distribution was developed to define the likelihood of different quantities of annual valleywide runoff. This distribution can be used to define the statistical significance of a particular “wet” or “dry” year.

Tributary streams in the Owens Valley lose between 35 and 99 percent of their annual discharge while flowing over the alluvial fan and volcanic deposits. Most of this loss recharges the ground-water system; much less is evapotranspired. The seepage rate for a stream typically decreases with increasing discharge; however, in the Owens Valley, the diversion of high flows onto alluvial fans to enhance recharge has resulted in a fairly constant seepage rate for individual streams. Linear runoff-recharge relations that were developed for each tributary stream using these seepage rates can be used to predict likely ground-water recharge for different quantities of valleywide runoff.

The Owens River gains water from ground-water seepage along most of its length in the Owens Valley. Since about 1970, however, the river has begun losing water to the aquifer system near the Big Pine well field. A similar condition may soon occur near the Laws well field. Surface water probably also seeps into the ground beneath the Tinemaha Reservoir. The lower Owens River gains water from the aquifer system, but much of this water is used to support riparian vegetation covering most of the nearly dry river channel. The Los Angeles Aqueduct, an unlined channel through much of the Owens Valley, gains water from the aquifer system, except where the aqueduct rises from the valley floor south of Independence. Between Independence and the Alabama Hills, the aqueduct loses water to the aquifer system. From the Alabama Hills to the Haiwee Reservoir, a concrete liner restricts any significant interaction between the aqueduct and the aquifer system.

**Structure of the Aquifer System.**—The ground-water system of the Owens Valley includes all permeable valley-fill deposits within the Owens Valley graben and is bounded by the welded members of the Bishop Tuff on the north and by the impermeable metamorphic and igneous rocks of the Sierra Nevada on the west, the White and the Inyo Mountains on the east, and the Coso Range on the south. The ground-water system is composed of two structurally separated depositional basins—the Bishop Basin to the north and the Owens Lake Basin to the south. The two basins are joined just south of Big Pine. This juncture is formed by a structural offset in graben-bounding faults, by a gentle rise in the underlying bedrock, by an upthrown piece of bedrock (Poverty Hills), and by the presence of volcanic deposits that intermittently have blocked the downvalley flow of water and sediment. Just north of the juncture, an 80-ft thick, tight blue-green clay identified by test drilling indicates that a lake was present at the south end of the Bishop Basin during some period(s) of accumulation of valley-fill sediment.

The aquifer system is defined as the most active part of the ground-water system and includes an unconfined member (hydrogeologic unit 1), a confining member (hydrogeologic unit 2), and a composite confined member (hydrogeologic unit 3). The aquifer system extends from the south side of the Volcanic Tableland to the north side of the Owens Lake. Below the aquifer system are poorly transmissive unconsolidated deposits (hydrogeologic unit 4).

The aquifer system was conceptualized with the aid of depositional models that defined the type and location of deposits within the basin. Previously unidentified transition-zone deposits, which are not present at land surface, were suggested by the depositional models and were found to play a dominant role in ground-water movement. The depositional models were aided by the discovery of lake deposits (blue-green clay) in the Bishop Basin and were especially useful in extending data and concepts to areas with sparse or missing data.

Faulting throughout the Owens Valley is important in controlling ground-water movement. The Owens Valley Fault restricts flow from west to east across the fault; thus, flow on either side of the fault is channeled south toward the Owens Lake. A previously unidentified fault adjacent and roughly parallel to the aqueduct in the Owens Lake Basin also restricts movement of ground water from west to east. More ground water is stored in alluvial fan deposits to the west because of this restriction. On the north side of the Alabama Hills, faults and a shallow depth to bedrock restrict ground-water movement. As a result, ground water in the vicinity of the Alabama Hills is forced to flow as far north as Independence before reaching the valley floor.

Faults near Big Pine are related to major structural movement. A fault whose primary trace crosses Crater Mountain and the alluvial deposits of Big Pine Creek restricts ground-water movement in the alluvial deposits, but it produces an extremely transmissive fracture zone in the volcanic deposits of Crater Mountain. Several other minor faults that restrict ground-water movement have been identified throughout the valley, and the major structural movement that formed the Owens Valley undoubtedly created many other faults that are hidden from view. The installation and operation of future monitoring and production wells, particularly west of Bishop and near Lone Pine, may identify additional faulting that affects ground-water flow.

**Ground-Water Recharge and Discharge.**—Ground-water recharge to the aquifer system occurs primarily from tributary streams; mountain-front runoff between tributary streams; canals, ditches, and ponds; and irrigation and watering of livestock. Lesser quantities of recharge occur from spillgate releases, underflow, and direct precipitation. Ground-water discharge occurs primarily from pumped and flowing wells; evapotranspiration; and underflow out of the aquifer system. Lesser quantities of discharge occur from springs and seeps and from channel seepage to the river–aqueduct system and the lower Owens River.

Both underflow into the aquifer system from Round and Chalfant Valleys and underflow out of the aquifer system into the Owens Lake area are significantly less than prior estimates. Ground-water flow through the permeable layers of the Bishop Tuff and into the aquifer system is minimal. Ground-water flow into the aquifer system from the north is limited by the small quantity of recharge that is available and by the moderately transmissive deposits near the boundaries. Ground water that flows out of the aquifer system to the south crosses the boundary of the aquifer system and eventually is discharged by flowing upward through many fine clay and silt layers in the Owens Lake bed or by flowing from springs and seeps along the toes of alluvial fans bordering the Owens Lake.

In 1970, pumpage was increased from an average of about 20,000 acre-ft/yr to more than 98,000 acre-ft/yr in order to provide water for export in the second aqueduct. Pumpage commonly exceeded 130,000 acre-ft/yr, and in water year 1972, pumpage exceeded 175,000 acre-ft/yr. Also in about 1970, the allocation of water for irrigation and livestock in the valley was decreased, resulting in less recharge from those operations. The combination of these changes in water use caused significant changes in other components of ground-water recharge and discharge. Evapotranspiration decreased from about 112,000 acre-ft/yr during water years 1963–69 to 72,000 acre-ft/yr during water years 1970–84; discharge from springs and seeps decreased from about 26,000 acre-ft/yr to 6,000 acre-ft/yr; ground-water discharge to the river–aqueduct system decreased from about 16,000 acre-ft/yr to 3,000 acre-ft/yr; and storage in the aquifer system was depleted by about 8,000 acre-ft/yr.

Detailed measurements of evapotranspiration, transpiration, and leaf area were made at several study sites throughout the Owens Valley. These data confirm that transpiration by native vegetation is proportional to the quantity of vegetative biomass (leaf area). The data also show that evapotranspiration consists primarily of transpiration by native vegetation. Therefore, the substantial change in evapotranspiration that occurred from about 1970 to 1984 reflects a nearly equivalent change in the quantity of native vegetation. Changes in native vegetation induced by increased pumping beginning in 1970 probably were accentuated by the drought of 1976–77. At some point between 1970 and 1978, water use per acre of native vegetation decreased about 25 percent.

By 1988, pumping capacity was increased again, this time to provide water to enhance or mitigate selected sites where native vegetation was adversely affected by previous increases in pumping. In water years 1987–88, total pumpage—for in-valley uses, export, and enhancement and mitigation—exceeded 175,000 acre-ft/yr. This increase in total pumpage, whether for export or mitigation, will further decrease total evapotranspiration and the total biomass of native vegetation in the Owens Valley.

The successful extraction of ground water from the Owens Valley has been aided by locating the wells in transition-zone and volcanic deposits. Pumping within the transition zone causes water to be withdrawn from western alluvial fans, which have a large areal extent and high specific yield and serve as extremely useful underground reservoirs. Well yields commonly exceed 6 $ft^3/s$ from the highly transmissive (21,000 $ft^2/d$) transition-zone deposits and 15 $ft^3/s$ from the exceptionally transmissive (greater than 200,000 $ft^2/d$) volcanic deposits. The large capacity of many production wells in the Owens Valley makes them comparable in size (volume of flow) with the smaller streams in the valley and accentuates their effect on the aquifer system.

**Ground-Water Movement.**—Ground water moves from areas of recharge to areas of discharge. In the Owens Valley, ground water generally moves from the sides of the valley toward the center, and from north to south. Pumping from several well fields in the valley captures some of the ground water before it reaches the center of the valley. Most ground water that is not captured by the well fields is discharged as evapotranspiration or flows into the river–aqueduct system or the lower Owens River. Ground water that is recharged on the sides of the valley moves vertically down through moderately transmissive deposits, and then horizontally into either the unconfined member (hydrogeologic unit 1) or the composite confined member (hydrogeologic unit 3) of the aquifer system. Along the sides of the valley, the vertical hydraulic gradient is downward; in the center of the valley, the vertical hydraulic gradient is upward, with a head difference of as much as 30 ft.

Along the sides of the valley, horizontal hydraulic gradients are steep and ground water flows rapidly through the alluvial fan or volcanic deposits. Beneath the valley floor, horizontal ground-water gradients are exceptionally flat, except near pumped wells, and ground water moves slowly toward discharge locations. Flow from hydrogeologic unit 3 to hydrogeologic unit 1, or vice versa, occurs very slowly through confining clay layers (hydrogeologic unit 2), or more rapidly through the gravel pack or casing of unpumped wells.

The water table beneath the valley floor is maintained at a nearly constant altitude. Native vegetation, springs, and surface-water bodies on the valley floor act as hydraulic buffers to minimize changes in water-table altitude through changes in recharge and discharge. A small rise in the water table results in increased discharge to evapotranspiration by native vegetation, to springs, and to surface-water bodies. A small decline in the water table results in decreased discharge and, in areas where ground water drops below the level of surface-water bodies, to increased recharge from the surface-water bodies. In contrast, the water table beneath the alluvial fans fluctuates markedly from one year to another as a result of changes in the quantity of recharge and pumpage; the hydraulic buffers on the valley floor are too distant to make a noticeable difference.

As a result of hydraulic buffering, the water table beneath the valley floor was at approximately the same altitude in 1984 as it was prior to 1970 except in two locations—near Big Pine and near Laws. In those areas, large quantities of pumpage resulted in a water-table decline of as much as 20 ft. This decline was greater than the effective range of buffering by nearby spring discharge and evapotranspiration. It was mistakenly assumed at the outset of the cooperative studies that a similar water-table altitude implies a similar condition of the aquifer system. However, the results of this study show that the same, or nearly the same, water-table altitude is possible with two substantially different combinations of recharge and discharge. In the Owens Valley, changes in vegetative cover, evapotranspiration, discharge from springs and seeps, and recharge from the river–aqueduct system and the lower Owens River have compensated for changes in water-table altitude.

Although ground-water levels are relatively flat over much of the valley floor, drawdown cones do form near the well fields. Typically, the cones elongate up and down the transition-zone deposits, broaden up the alluvial fans, and steepen toward the valley floor. This asymmetric shape is caused by the linearity of the transition-zone deposits combined with the high storage of the alluvial fans and the less transmissive deposits and faults toward the center of the valley. In the southern part of the Owens Lake Basin, drawdown cones near well fields are even more severely deformed by the presence of a barrier fault near the aqueduct.

If pumping rates are sufficiently high from a line of wells in the transition-zone or volcanic deposits, then a pumping trough is formed that limits or prevents ground water from flowing into hydrogeologic unit 1, which is an important source of water for native vegetation. Under more moderate pumping conditions, drawdown cones still extend up into the western alluvial fans and decrease the quantity of ground water flowing horizontally into hydrogeologic units 1 and 3 beneath the valley floor. Drawdown cones produced on the west side of the Bishop Basin and northern part of the Owens Lake Basin extend beneath confining clay layers and induce ground-water movement from alluvial fans on the east side of the valley. This effect is most evident near Big Pine because of the extraction of an exceptionally large quantity of ground water and the presence of the 80-ft-thick blue-green clay layer overlying the pumped zone.

**Ground-Water Flow Model.**—Development and calibration of the valleywide ground-water flow model confirmed the general conceptualization of the aquifer system as presented by Hollett and others (1991). Use of the model also confirmed that the Owens Valley aquifer system has been in a transition caused by increased pumping and changes in water use that were prompted by increased water exports beginning in 1970. Model simulations suggest that as of 1988 the transition is not complete.

Design of the valleywide model, which simulates the aquifer system, includes two layers, a finite-difference grid consisting of 180 rows and 40 columns, and uniform square model cells with a dimension of 2,000 ft on each side. Transmissivity is temporally constant and is spatially defined by about 20 model zones; storage coefficients are temporally and spatially constant. The model zones are based on hydrogeologic units and subunits. The model uses annual stress periods with many discrete recharge and discharge components—some simulated as specified fluxes, and some simulated as head-dependent relations. The model was calibrated for water years 1963–84 and verified for water years 1985–88. Four additional simulations were based on hypothetical future conditions and were used to evaluate selected water-management alternatives.

Prior to development of the valleywide model, several preliminary models with different scales and levels of complexity were developed to test particular questions about the aquifer system or about methods of simulating the aquifer system. This modeling approach proved to be most valuable. Understanding of both the model and the aquifer system was greatly improved and a more accurate and useful valleywide model was obtained.

An important benefit of using the valleywide ground-water flow model is that it can be used to calculate an annual value for hydrologic components (such as valleywide evapotranspiration from the aquifer system, streamflow gains and losses, and change in ground-water storage) that either are not measured routinely or are extremely difficult to measure. The model also enables the separation of multiple coincident stresses on the system, such as extremely high runoff occurring in 1969 at nearly the same time as the significant increase in valleywide pumpage in 1970. Analysis of how recharge and discharge components of the aquifer system changed from 1963 to 1988 provided as much insight into the operation of the aquifer system as did the concurrent analysis of measured ground-water levels and computed heads.

Sensitivity analysis of the ground-water model showed that pumpage is the dominant stress in the aquifer system both near well fields and in recharge areas. Away from recharge areas and well fields, such as in the area between Bishop and Big Pine, neither recharge nor pumpage has a significant effect on simulated heads. Surprisingly, the model was not sensitive to the vertical distribution of pumped water. The match with measured ground-water-level data when all the pumpage was from the lower model layer was similar to the match when pumpage was divided between the layers. During short-term aquifer tests, the vertical distribution of pumpage has been shown to be important; however, this lack of sensitivity shown by the model indicates that over a longer period of time the quantity of pumpage is more important than the design or location of wells.

Results from the simulations indicate that since 1963 the water table has declined beneath much of the western alluvial fans, particularly in the Taboose–Aberdeen area. Only a couple of monitoring wells, however, are present on the fans to confirm this result. In the Taboose–Aberdeen area, model simulations indicate that the water table beneath the alluvial fans has declined as a result of increased ground-water pumping, even though the water table beneath the valley floor has changed very little. This decline in water-table altitude beneath the fans results in a decrease in evapotranspiration by native vegetation on the valley floor and implies that a reduction in the biomass of native vegetation in the area is occurring now (1988), or will occur soon.

**Water Management.**—In many ways, the water management of the Owens Valley has been optimized over time. Purposeful diversion of tributary streams on the alluvial fans has enhanced natural recharge. Siting wells in the most transmissive deposits in the valley and near the dominant sources of recharge has increased management flexibility. The quick and easy answers to improved water management are largely gone.

Present water-management considerations in the Owens Valley include both the needs and desires of residents of the valley, and of Inyo County and the Los Angeles Department of Water and Power. Water operations are constrained by water-supply needs both in the valley and in Los Angeles and by variations in water-supply availability both in the valley and throughout much of the Southwestern United States. Native vegetation is resilient to short-term changes in the availability of water but requires a replenishment of soil moisture at least every 2 years, commonly by capillarity from the saturated aquifer system. Recharge of the aquifer system is constrained by the physical capacity to transport surface water and by the transmissivity of the surficial materials. The control and distribution of excess surface water also is constrained by air-quality restrictions related to the desiccation of the Owens Lake bed.

Selected water-management alternatives for the Owens Valley were analyzed both with the aid of hydrologic data and interpretations gained during the cooperative studies and with simulations using the valleywide ground-water flow model. Four water-management alternatives simulated with the model were: (1) a steady-state simulation of conditions in 1988; (2) the same steady-state simulation as alternative 1, but with variations in recharge of plus or minus 10 percent; (3) the same steady-state simulation as alternative 1, but with variations in pumpage using 25-percent increments of average pumpage; and (4) a 9-year transient simulation using 3 sequential years each of drought, average, and wet conditions.

Results from the simulations indicate that significant changes in water-table altitude and evapotranspiration will result if average pumpage exceeds about 75,000 acre-ft/yr. If increased pumpage is distributed to existing wells, changes in water-table altitude will occur in nearly all areas of the valley except in the unstressed area between Bishop and Big Pine and east of the Owens River. Long-term variations in recharge of plus or minus 10 percent have relatively little effect in comparison with variations in pumpage. These minor variations in long-term recharge were used to evaluate the effects of climatic cycles or changes in climate.

The results of alternative 4 were instructive for several reasons. Not surprisingly, the simulated effects of a 3-year drought are propagated to all areas of the aquifer system. Water-table declines are greatest near well fields, in particular Big Pine, Independence–Oak, and Laws. What is surprising is how long these changes in the water-table altitude persist. Significant drawdown in the water table continues through 3 years of average conditions, and some drawdown continues through 3 subsequent years of above-average recharge. These results imply that changes in native vegetation (water use and biomass) still may be occurring several years after a significant water-table decline caused by drought or pumping.

The transient simulation also indicated areas of the valley (Laws, Taboose–Aberdeen, and Independence–Oak well fields) where alterations in recharge and pumping could minimize the adverse effects of water-table decline. These areas have native vegetation and significant water-table fluctuations; either pumping would need to be reduced or recharge would need to be increased if a long-term reduction in native vegetation is to be avoided.

Alternative methods of water management that can minimize the adverse effects of pumping on native vegetation are limited to a few choices. In general, the alternative methods will be most effective in providing short-term benefits and increased flexibility in water management. Some alternative methods may create a localized benefit, but they may adversely affect native vegetation in other areas of the valley.

Storing additional ground water beneath the alluvial fans and volcanic flows will provide additional water in subsequent years; however, the higher ground-water levels will induce increased discharge of ground water from springs and seeps and from native vegetation as evapotranspiration. Increasing recharge for tributary streams that presently have low recharge rates may be possible. Volcanic deposits present opportunities for exceptionally high recharge and pumping rates, but the high transmissivities and low storage of the volcanic flows tend to limit their usefulness for long-term water management. The volcanic zones fill fast, but also drain fast. By recharging more water, higher on the alluvial fans, the time lag between ground-water recharge and discharge can be increased.

Siting new production wells on the alluvial fans or volcanic deposits will limit the short-term effects of pumping on native vegetation. Over time, however, as drawdown cones extend toward the valley floor, native vegetation may be affected by the decline in ground-water levels several thousand feet away. Drilling on alluvial fans may be difficult and well yields will be less than for comparable wells in more transmissive deposits.

The most promising long-term water-management alternative for the Owens Valley—one that provides ground water for export and minimizes adverse effects on native vegetation—is increasing extractions from the Bishop Creek alluvial fan (Bishop Cone). Land on the valley floor near the Bishop Cone either is urban or is manipulated with water-spreading and canals. However, as of 1988, export of ground water from the Bishop Cone is not permitted as a result of the Hillside Decree. This legal decision requires that ground-water extractions from the Bishop Cone be used in the immediate area and not be exported to other areas of the Owens Valley or out of the valley to Los Angeles.

The potential for development of a well field south of Bishop and north of Big Pine is promising. Highly transmissive transition-zone deposits may be present along the western side, and possibly eastern side, of the valley. However, the lack of significant recharge may limit production and accentuate drawdowns. The absence of horizontally extensive fine-grained deposits in the area will cause more rapid decline of the water table and probably greater adverse effects on native vegetation than would occur in most other areas of the valley.

Additional water development in the Laws area is limited by the minimal quantity of local recharge and by the absence of horizontally extensive fine-grained deposits. In this and other areas of the valley, unlined surface-water features, such as canals and ditches, provide an important source of local recharge; continued use of them will minimize adverse effects on native vegetation. Additional pumpage from the Big Pine well field is limited by natural inflow. Deeper wells might tap previously unknown volcanic deposits and derive water from storage; the pumped water could be replaced in years of above-average runoff using the abundant flow of Big Pine Creek and the highly transmissive volcanic deposits. Ground-water pumpage on the east side of the lower Owens River may be possible, but long-term yield is dependent on additional artificial recharge. Potentially poor ground-water quality also is a concern. Development of a well field near the Lone Pine area is limited by the presence of abundant fine-grained deposits and the lack of recharge. Development of some well production south of Lone Pine may be possible hydraulically, especially if transition-zone deposits are present beneath alluvial fans on the west side of the Owens Lake, but excessive pumpage likely will induce the migration of poor-quality water from the lake.

Development of new production facilities or further use of artificial recharge in the Owens Valley will increase water-management options and may provide a means of mitigating the adverse effects of pumping on native vegetation. However, one attribute of a more intensively managed aquifer system is that the distribution of native vegetation will be less even. The natural flow of the aquifer system tends to smooth out ground-water levels, recharge, and discharge. Human changes to the aquifer system tend to focus recharge and discharge into smaller areas. As the valley becomes more actively managed, it will become more pod-like, with pods of thriving vegetation near enhancement and mitigation projects and pods of highly stressed vegetation near wells. In between, less water will be available to native vegetation than was available prior to the increase in water development.

Rotation of pumpage among the several well fields is one method of optimal water management that facilitates the local recovery of the aquifer system. As a drought continues, a couple of weeks or months of replenishment of soil moisture may be extremely important in maintaining the health of native vegetation. Rotational pumpage, which allows recovery of the water table and replenishment of soil moisture in the root zone, probably is the most promising short-term water-management technique.

The most innovative water-management options for the Owens Valley may include conjunctive operations with other ground-water basins between the Owens Valley and Los Angeles. Water-banking along the aqueduct may be one way to capture water during periods of above-average runoff, save it for drier periods, and limit the adverse effects of pumping on native vegetation in the Owens Valley.

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