EVALUATION OF SELECTED WATER-MANAGEMENT ALTERNATIVES

An evaluation of alternative methods of water management involves an appraisal of the present (1988) operating conditions and the physical and social constraints that restrict changes in operations. This evaluation recognizes the social constraints, but focuses on the hydrologic constraints, recognizing that although social constraints might seem to be more encumbering, they often are far less static than the physical constraints presented by precipitation, streamflows, and the aquifer system. Much of the evaluation relies on simulation results from the valleywide ground-water flow model to quantify the likely effects of different management alternatives.

General Water-Management Considerations

Water management of the Owens Valley involves a complex array of conflicting needs and desires. The residents of the Owens Valley need water for local uses such as ranching and domestic supply. Many of the residents desire that water be used for the aesthetic aspects of the valley such as flowing streams and to provide the water needs of native vegetation. The Los Angeles Department of Water and Power, although recognizing these local needs and desires, has continuing needs to export water to Los Angeles. As regional water supplies dwindle and the population of southern California increases, Los Angeles may desire to export additional high-quality water from the Owens Valley. In the difficult task of balancing conflicting needs and desires, the emotional side of water-management issues often tends to take precedence over otherwise purely technical issues.

The goals of water management in the Owens Valley consist of fulfilling both needs and desires. The primary goals include supplying sufficient water for local domestic, ranching, and municipal uses; for native vegetation and aesthetics; and for export to Los Angeles. Secondary goals include mitigation of pumping effects on native vegetation in the immediate area of wells and enhancement of selected areas of the valley. Inherent in achieving these secondary goals, if other water-management practices are continued, is an acceptance of a likely overall decrease in the quantity of native vegetation in other areas of the valley. An ongoing management goal since 1970 has been to decrease consumptive use of water on ranches and lands leased by the Los Angeles Department of Water and Power and to use water more efficiently throughout the valley. Achievement of each of these goals is limited by a variety of considerations that constrain water management in the Owens Valley. The major considerations are described below.

Regional water supplies.—The Owens Valley is part of a much larger network of water supplies, transport, and use. In southern California, water is obtained from a limited number of sources, primarily from northern California, the Colorado River, and the Owens Valley. The use and export of water from the Owens Valley must be viewed within the larger issues of water supply and demand within the arid Southwest, particularly southern California.

Export of surface and ground water.—Water-gathering activities along the aqueduct, primarily north of the Owens Valley in the Mono Basin and the Long Valley, contribute to the total export of water to Los Angeles. A series of reservoirs and ground-water basins along the aqueduct system between the Mono Basin and Los Angeles are used to regulate flow and to store water from one year to the next. Because these storage capacities, in general, are limited, a nearly constant export of water from the Owens Valley is desired. Since 1970, ground-water withdrawals from the Owens Valley have been used to augment surface-water diversions. In an average-runoff year, some ground water typically is exported; however, in a below-average runoff year, the quantity of ground-water exported out of the valley is increased significantly to make up for the shortage in surface water.

Antecedent conditions from the previous water year affect the quantity of export desired by the Los Angeles Department of Water and Power. If antecedent conditions are dry, then less water is stored in reservoirs and ground-water basins along the aqueduct system, and more water is needed from the Owens Valley. As shown in figure 18, the antecedent conditions in turn affect the quantity of ground water that is pumped. If the preceding year has had average or above-average runoff, then ground-water pumpage is less.

The exportation of water from the Owens Valley to Los Angeles has been the subject of many controversies and lawsuits. Historically, California water law has been interpreted to require maximum beneficial use of water (State of California, 1992). In the early 1900's, beneficial use was nearly synonymous with reclamation of the land for farming and for industrial and municipal use. Since about 1970, the historical beneficial uses of water have been constrained by various environmental issues, such as preservation of phreatophytic vegetation in the Owens Valley and the maintenance of lake levels in the Mono Basin for wildlife habitat. Complying with environmental constraints and satisfying requirements of the California Environmental Quality Act (CEQA) play an increasingly critical role in the export of water from the Owens Valley.

Local use of water.—Water use within the Owens Valley includes commitments of water to each of the four major towns, four Indian reservations, three fish hatcheries, and many ranches (fig. 1, pl. 3, and table 11; Hollett and others, 1991, fig. 5). More recently, additional surface and ground water has been committed to maintain several enhancement and mitigation projects. These relatively high-water-use projects are scattered throughout the valley and provide maintenance of pastureland, wildlife habitat, and riparian vegetation.

Water management in the Owens Valley also has been affected by litigation, particularly the "Hillside Decree" (Los Angeles and Inyo County, 1990a, p. 5–16). This legal injunction required that ground-water pumpage in the Bishop area be used locally within an area extending from north of Bishop to just north of Klondike Lake (fig. 11). Within this area, which is referred to as the "Hillside area" or "Bishop Cone," no ground-water pumpage can be exported to other areas of the valley, or out of the valley to Los Angeles. Although the injunction protects the Bishop area, it severely constrains water-management options for the valley as a whole. The Bishop area has the most abundant native water supplies of any area of the valley as indicated by the large discharge of Bishop Creek (average annual discharge is more than 90 ft^3/s). Even if local residents, the Inyo County water managers, and the Los Angeles Department of Water and Power should agree on extracting additional ground water from the Bishop area to compensate for reducing ground-water pumpage from another area of the valley, the injunction prevents this reallocation of water.

Hydrologic considerations.—Water management within the Owens Valley also is constrained by physical limitations. Streamflow varies within each year, as well as from year to year. During some high-flow periods, not all streamflow can be captured for export or recharged to the ground-water system. During drier periods, minimum flows in the tributary streams may be required to maintain fish populations, and ground-water-recharge operations may be restricted. Some tributary streams, such as Oak Creek, have a large discharge, but a relatively small alluvial fan to be used for ground-water recharge. Other streams, such as Shepherd Creek, have a small discharge and a large alluvial fan.

Antecedent conditions affect the saturated ground-water system. As much as a 3- to 12-month delay occurs in the effect of an above-average runoff year on ground-water levels and discharge rates (well 1T, pl. 1; spring discharge, fig. 21). This means that above-average runoff will mitigate some of the adverse effects of a drought that occurs the following year. Ground-water levels beneath the valley floor will tend to rise at the same time as there is a need for additional ground water by native vegetation. The adverse effects of an extended dry period, however, will not be counteracted immediately by an above-average runoff year; the delay in recharge essentially extends the drought for an additional 3 to 12 months.

Antecedent conditions for the unsaturated zone are equally important in water management, as determined during the cooperative vegetation studies (Groeneveld and others, 1986a). In particular, the quantity of water in the unsaturated zone that is carried over from one year to the next is a primary indicator of whether native vegetation will remain healthy (Groeneveld and others, 1986b; Sorenson and others, 1991). As a result of this finding, past water-management practices may need to be altered. For example, ground-water pumpage could be restricted whenever antecedent soil-moisture conditions are too dry.

Simulation of Selected Water-Management Alternatives

The valleywide ground-water flow model was used to evaluate selected water-management alternatives for the Owens Valley. The specific alternatives described in table 14 were chosen after discussion with the technical staffs of Inyo County and the Los Angeles Department of Water and Power. The primary items of concern to valley residents and water managers were the long-term effects of continuing present (1988) operations (alternative 1); the effects of less runoff resulting from long-term climatic cycles or change in climate (alternative 2); the effects of long-term variations in average pumpage (alternative 3); and the ways to mitigate effects of a severe drought and to take

Table 14. Simulated water-management alternatives for the Owens Valley, California

[na, not applicable, because the solution does not depend on initial head]

Simulated water-management alternative	Description	Type of simulation	Initial conditions	Related figures (number)
1	Continue 1988 operations	Steady state	na	26 and 27
2	Continue 1988 operations with variations in recharge of plus or minus 10 percent of the 1988 steady-state value. Simulates long-term change in climatic conditions.	Steady state	na	28
3	Continue 1988 operations with variations in pumpage from 0 to 125 percent of the 1988 steady-state value.	Steady state	na	29
4	A 9-year sequence consisting of: 3 years of drought 3 years of average conditions 3 years of wet conditions.	Transient (9 years).	Results for water-management alternative 1.	30, 31, 32, and 33

advantage of unusually wet conditions (alternative 4). The first three alternatives were simulated with steady-state conditions; the fourth alternative was a 9-year transient simulation.

Because water management in the Owens Valley is exceptionally intricate—involving more than 40 streams, 30 canals, 600 gaging stations, and 200 production wells—the alternatives were designed to simulate general valleywide conditions in order to illustrate how the overall system responds. More detailed site-specific investigations, such as predicting the effects of managing selected wells or streams, are being conducted as part of ongoing water-management activities by Inyo County and the Los Angeles Department of Water and Power.

Alternative 1: Continue 1988 Operations

Alternative 1 addresses the question, “What will happen if present (1988) operations are continued?” That is, what will be the average condition (steady state) of the aquifer system if operations as of 1988 are continued for a long time, probably tens of years? To aid in defining 1988 operations and in evaluating the difference between present and past water-management practices, general water use in the Owens Valley since about 1900 was summarized. Periods with relatively similar characteristics of water use, and therefore relatively similar operation of the surface-water and ground-water systems, were identified (table 4). Results of this analysis were used in selecting appropriate time periods to calibrate and verify the ground-water flow model, as well as in identifying how 1988 conditions were different from past operations, even those as recent as the early 1980's.

Changes in water-management operations undoubtedly will be made as the hydrologic system and native vegetation of the Owens Valley are more fully understood. An important caveat in viewing the “1988 conditions,” as defined in this report, is that the study period was a time of considerable change, or proposed change, in water-management practices. Wide-ranging discussions between Inyo County and the Los Angeles Department of Water and Power typify the process of developing a joint water-management plan for the valley. Possible changes in water management being discussed include discharging a small quantity of water down the lower Owens River to maintain wildlife habitats along the river; installing new wells or using surface-water diversions to provide water for additional enhancement and mitigation sites; and installing new production wells with perforations only in the lower zones of the aquifer system (hydrogeologic unit 3)—not in hydrogeologic unit 1 where effects on the water table and native vegetation are more direct. Additional pumpage for enhancement and mitigation projects may prompt a reduction in pumpage for other uses, including export. Thus, the 1988 conditions as defined in this report likely will evolve over time as understanding of the hydrology of the Owens Valley improves and negotiations between Inyo County and the Los Angeles

Department of Water and Power continue. Nevertheless, the 1988 conditions as defined in this report represent the best estimates of future operations based on information available in 1988, and most results based on this definition will not be changed significantly by minor changes in local operations.

Average 1988 conditions in the Owens Valley were defined using a combination of long-term historical data (water years 1935–84) and selected recent data (water years 1985–88) that reflect recent water-management practices (tables 4 and 11). The selection of specific values for the ground-water flow model can be grouped into four categories depending on how static each item has been.

Long-term average relations.—A long-term average period, water years 1935–84, was used to define average-runoff conditions. The relations of runoff to ground-water recharge for tributary streams (fig. 13) and for ungaged areas (table 11), both of which were used to simulate ground-water conditions during water years 1963–88, were assumed to remain valid for future conditions.

Long-term constant values.—Underflow and recharge from precipitation were held constant as they had been during simulation of water years 1963–88 (table 11).

Recent constant values.—Recharge from irrigated areas was the same as the constant values used during simulation of water years 1970–88. This period reflects the change in water use that occurred about 1970 (table 4). The maximum evapotranspiration rate was the same as that used to simulate water years 1978–88.

Recent average values.—A recent period (water years 1985, 1986, and 1988) was selected to represent average conditions for those items that were recently added or changed. The selection of these specific years included an evaluation of the probability of different percent-runoff years (fig. 12) and of the effect of antecedent conditions on pumpage (fig. 18). The selected period includes a wet water year (1986), an average water year (1985), and a dry water year (1988). This period was used to determine recharge from miscellaneous operations, recharge from water use on Indian lands, recharge from canals and ditches, and discharge from pumping. Pumpage from enhancement and mitigation wells, which were being installed during water years 1985–88, was planned to provide a virtually constant supply regardless of runoff conditions (R.G. Wilson, Los Angeles Department of Water and Power, oral commun., 1988). As a result, average pumpage for enhancement and mitigation wells was defined as the values for water year 1988. An important assumption regarding pumpage was that average pumpage for enhancement and mitigation projects was in addition to average pumpage for export.

These values of recharge and discharge defined for average 1988 conditions were used in the calibrated ground-water flow model to determine a steady-state solution of simulated heads, recharge, and discharge (table 11). The simulated change in water-table altitude between water year 1984 (fig. 19 and pl. 1) and 1988 steady-state conditions is shown in figure 26. Water year 1984 was chosen for comparison because ground-water levels were relatively high over most of the basin, most springs had resumed some discharge, and the ground-water basin was nearly as “full” as it had been prior to 1970 (Hollett and others, 1991). A comparison of water-budget components for the 1988 steady-state period with those for water years 1963–69 and water years 1970–84 is shown in figure 27. These three periods represent the main changes in the Owens Valley hydrologic system (table 4) since the early 1900's.

On the basis of the model simulations, changes in the 1984 water-table altitude and in recharge and discharge will occur if the 1988 operating conditions, as defined above, are continued. Most of the predicted water-table changes occur in the alluvial fan areas, particularly in the Taboose–Aberdeen and Independence areas (sections *C–C′* and *D–D′*, fig. 26). A large difference also is predicted in the Laws area and near Big Pine. The valley floor exhibits somewhat less change in the water table, as expected because of hydraulic buffers. Decreases in evapotranspiration and changes in the ground-water flow rate to or from the river–aqueduct system and the lower Owens River tend to minimize fluctuations in heads. On the valley floor, changes are characterized primarily by differences in recharge and discharge, as indicated by the simulated decrease in evapotranspiration (fig. 27 and table 11). Interestingly, total ground-water inflow is greater in the 1988 simulation (fig. 27) because a lower water table induces additional recharge from surface-water features. On the basis of observations made during calibration and verification of the ground-water flow model and during testing of water-management alternative 4, described later, reaching new steady-state conditions may require as much as from 10 to 20 years of similar operations (fig. 21 and pl. 1).

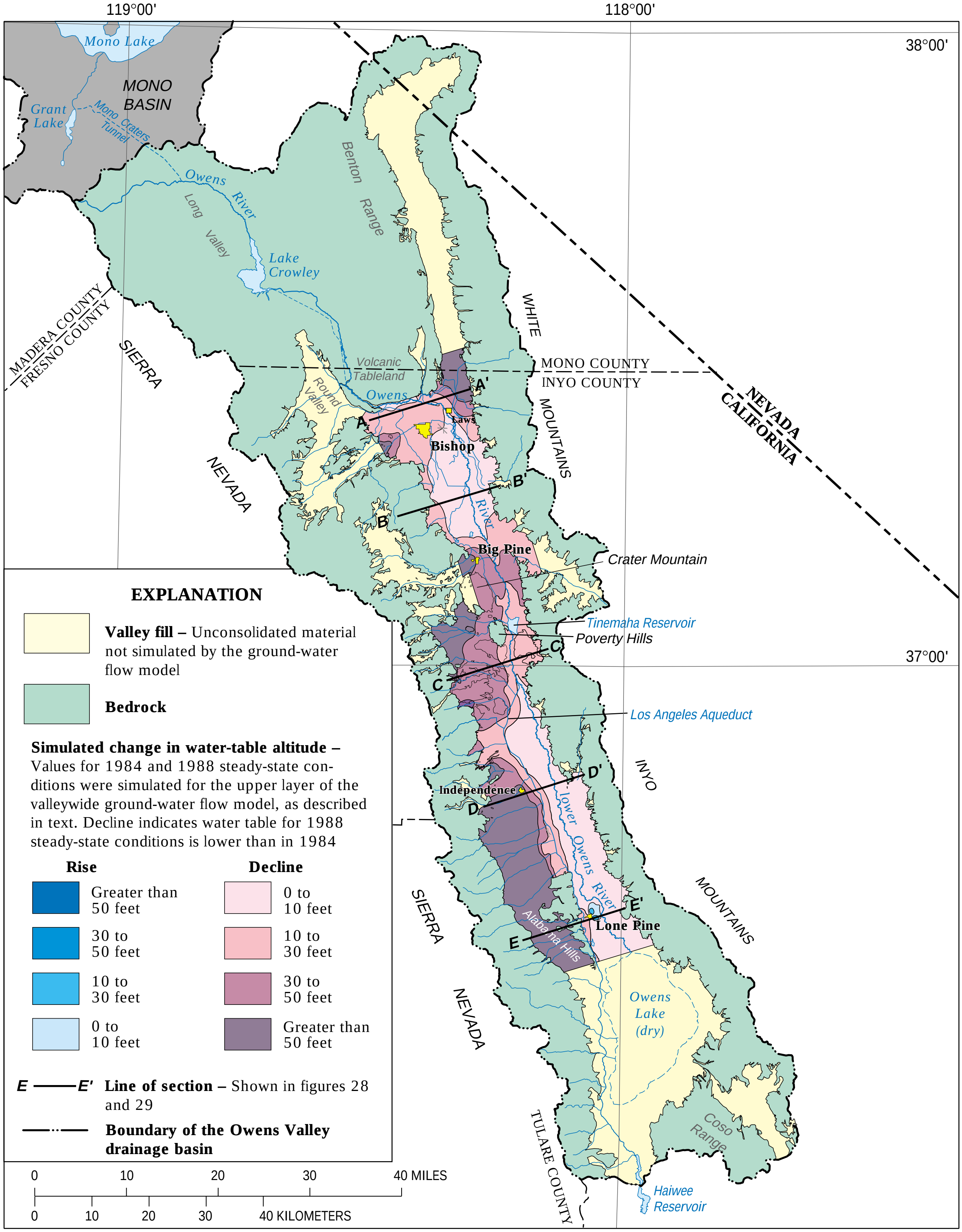

Figure 26. Simulated change in water-table altitude in the Owens Valley, California, between water year 1984 conditions and 1988 steady-state conditions.

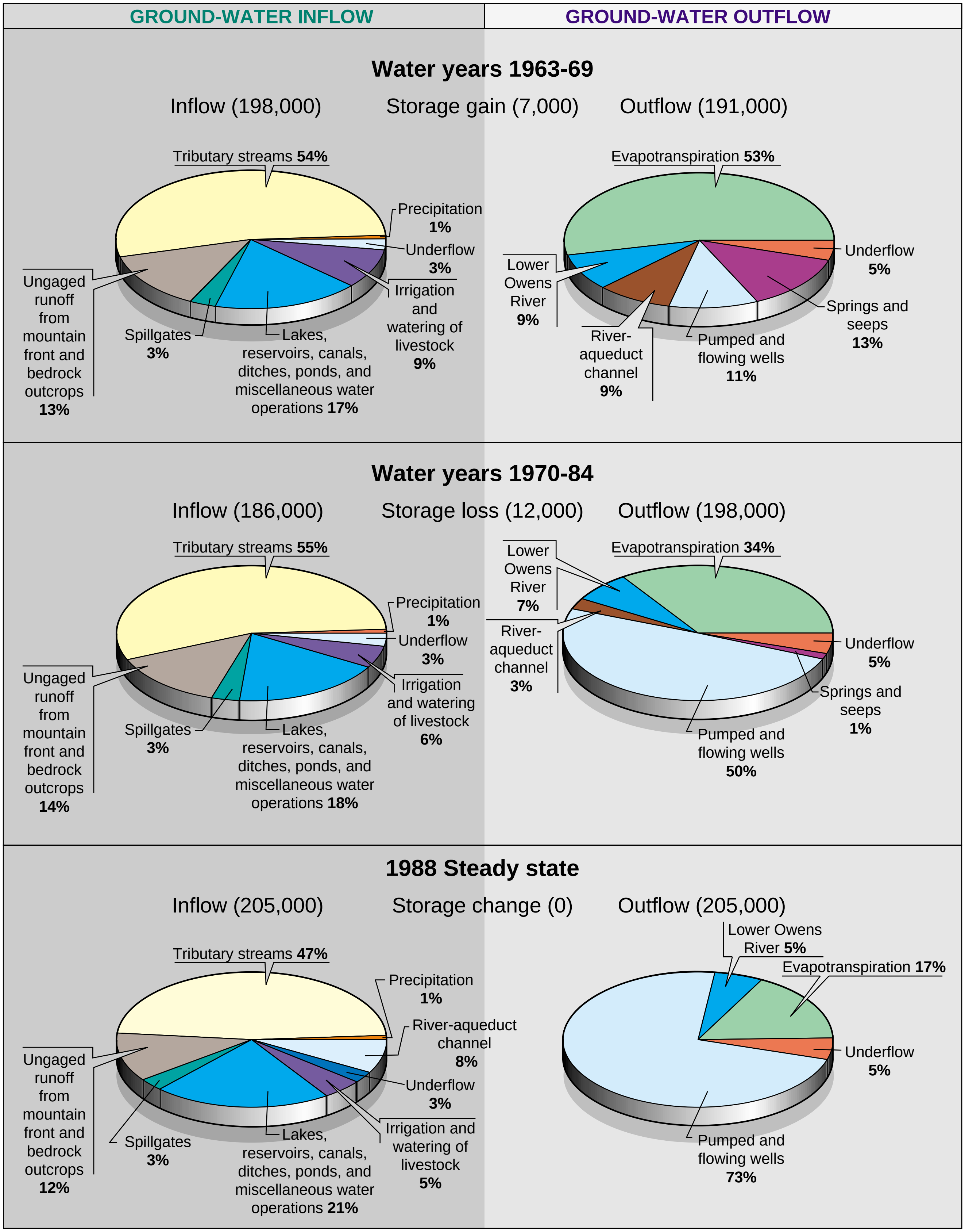

Figure 27. Simulated ground-water budgets for the aquifer system of the Owens Valley, California, for water years 1963–69, water years 1970–84, and 1988 steady-state conditions. Average inflow, outflow, and change in storage are expressed in acre-feet per year. Refer to text for model assumptions and to table 11 for precise values.

Table 15. Average pumpage from well fields in the Owens Valley, California

[ns, not simulated; wy, water years. Values in acre-feet per year. Values for 1-year responses are in excess of 1988 steady-state pumpage]

Time period	Well fields (figure 17)										
						Independence South					
	Laws	Bishop	Big Pine	Taboose–Aberdeen	Thibaut–Sawmill	Indepen-dence–Oak	Symmes–Shepherd	Bairs–George	Subtotal	Lone Pine	Total
1963–88 wy...	11,805	9,754	20,477	15,336	8,657	7,134	7,335	1,765	16,234	1,539	83,802
1963–69 wy...	5,290	6,091	668	1,783	339	3,382	2,044	327	5,753	259	20,182
1970–84 wy...	12,429	10,699	25,994	18,950	10,167	7,789	8,336	2,199	18,324	1,997	98,559
1985–88 wy...	20,868	12,623	34,453	25,505	17,549	11,245	12,842	2,651	26,738	2,062	139,798
1988 steady state.	29,391	11,962	37,113	22,386	21,169	11,497	11,500	1,952	24,949	2,305	149,275
1-year unit response (figure 34).	10,000	10,000	10,000	10,000	10,000	4,608	4,609	783	10,000	ns	60,000
1-year response (figure 35).	10,280	5,518	14,873	16,894	4,427	9,412	10,140	3,408	22,960	2,018	76,970

Although some uncertainty is present in the assumptions of this simulated steady-state condition, the general conclusions are not altered by slightly different assumptions about specific recharge or discharge components. The main difference between the 1988 steady-state values of recharge and discharge and previous values is the marked increase in ground-water pumpage, especially pumpage from enhancement and mitigation wells (table 11). An additional difference is that the long-term average runoff (100 percent of average runoff) assumed for the 1988 steady-state period is somewhat lower than that during water years 1963–84 (107 percent of average runoff).

The large increase in pumpage that occurred during water years 1970–84 was offset partially by a decrease in springflow, which helped to minimize changes in the water-table altitude. By 1984, total spring discharge was significantly less than it was prior to 1970, and the buffering effect on the water table was largely gone (fig. 21 and table 11). The further increase in pumpage assumed for the 1988 steady-state period combined with the slight decrease in average runoff resulted in a further decline of the water table in comparison with 1984 conditions (fig. 26).

During the initial part of this study, the 1984 water year was perceived to represent a return to relatively average conditions—water levels had returned to near the 1970 levels in most parts of the valley. However, this condition was highly contingent on the large runoff quantities of the late 1970's and early 1980's (fig. 12 and table 7) and the relatively lower pumpage (fig. 18). In contrast, the 1988 steady-state conditions assume long-term average runoff and a much higher quantity of average pumpage (table 15), albeit for various uses other than export out of the valley. If these assumptions remain valid, then the basin, as of 1988, is in the midst of another transition, one prompted largely by the increased pumpage from the enhancement and mitigation wells (table 11).

In general, the water-table decline is greatest in the alluvial fans, and least in the areas of seeps, drains, and surface-water bodies (hydraulic buffers) that are in contact with the ground-water system. The significant water-table decline in the alluvial fans will have no effect on overlying vegetation because the water table is many tens or hundreds of feet beneath the land surface of the fans, except in highly faulted areas, such as near Red Mountain or immediately north of the Alabama Hills (figs. 3 and 14). The water-table decline in the alluvial fans, however, will reduce the ground-water flow rate toward the valley floor, which in turn will reduce ground-water discharge, primarily transpiration from native vegetation on the valley floor. Plant stress similar to that observed by Sorenson and others (1991) can be expected to occur in areas near the toes of the fans and in parts of the valley floor near Big Pine and Laws if 1988 conditions are continued. It is important to note that there may be only a slight change in water-table altitude beneath these plants as a result of changes in plant transpiration and changes in flow to nearby seeps, drains, and surface-water bodies. This is a characteristic response of a ground-water system modulated by hydraulic buffers.

Changes in water management can offset some of the adverse effects implied in figure 26. Increased recharge of surface water during wet years, especially in or upgradient from areas likely to have decreased transpiration by native vegetation, would help to minimize a long-term reduction in native vegetation on the valley floor. In contrast to other nearby basins, however, the recharged water is not retained for an extended period of time (Danskin, 1990). The relatively high transmissivity of sand and gravel deposits and the exceptionally high transmissivity of volcanic materials tend to dissipate recharged water relatively fast (within a few years). In order to successfully mitigate the effects implied in figure 26, recharge needs to be increased above historical averages (figs. 21 and 27; tables 10 and 11) and pumpage probably needs to be decreased in selected areas where recharge cannot be increased.

Alternative 2: Continue 1988 Operations with Long-Term Changes in Climate

Alternative 2 addresses the question, “What if climatic cycles or long-term climatic change cause average basinwide runoff to be slightly less, or more?” The time period, water years 1935–84, that was used to analyze the surface-water system and develop runoff-recharge relations (fig. 13 and table 11), despite being 50 years long, may not be representative of average-runoff conditions for the next 25 to 50 years. Normal variations in climate could produce a change of a few percent in long-term average runoff. In addition, possible climatic change caused by human activities, although a highly controversial and largely unresearched topic (Danskin, 1990), is a recent global concern. The specific effects of induced climatic change are unknown; however, changes in the average annual runoff in basins in the Southwestern United States, including the Owens Valley, have been suggested (Revelle and Waggoner, 1983; Lins and others, 1988; Lettenmaier and Sheer, 1991). It also is possible that an induced climatic change may alter runoff conditions even more within individual years (Wigley and Jones, 1985; Moss and Lins, 1989), but this highly speculative aspect was not addressed in this study.

Simulation of alternative 2 used the 1988 steady-state conditions (alternative 1) with variations of plus or minus 10 percent in the average percent of runoff. This relatively small deviation reflects the generally well-known and stable condition of long-term average runoff. Also, the runoff-recharge relations are likely to remain valid for small changes in runoff. Analysis of a greater change in average runoff, which might result from more substantial changes in climate, would require a reinterpretation of precipitation patterns and amounts (fig. 7) and streamflow relations (fig. 13). In the present analysis, the quantities of ground-water recharge affected by the change in percent runoff include recharge from tributary streams, from mountain-front runoff between tributary streams, and from local runoff from bedrock outcrops within the valley fill (table 10). Recharge from precipitation was assumed to occur primarily during extremely wet years and was not changed. All other quantities of ground-water recharge and discharge were the same as those defined for alternative 1.

Results from alternative 2 are shown in figure 28 for representative sections across the valley. Sections *B–B′*, *C–C′*, *D–D′*, and *E–E′* in figure 28 correspond closely with hydrogeologic sections *B–B′*, *D–D′*, *E–E′*, and *F–F′*, respectively, of Hollett and others (1991, pl. 1 and 2). Also shown on the sections in figure 28 are simulated water tables for water year 1984 and for average runoff conditions (1988 steady-state simulation, fig. 26) and the range in simulated water tables for water years 1963–88. Only the simulated heads for the upper model layer (water table) are shown because they are most important in predicting effects on native vegetation; simulated heads for the lower model layer show a similar pattern, but with some vertical offset from heads for the upper model layer.

Most obvious in figure 28 is the difference between simulated steady-state conditions for 1988 (100 percent runoff) and simulated conditions for water years 1963–88. By comparison, variations of 10 percent in average basinwide runoff produced less difference in the water table in most areas of the basin, except along the western edge of the valley from Independence to Lone Pine (sections *D–D′* and *E–E′* in fig. 28). As expected, water-table differences resulting from variations in runoff are most pronounced in the

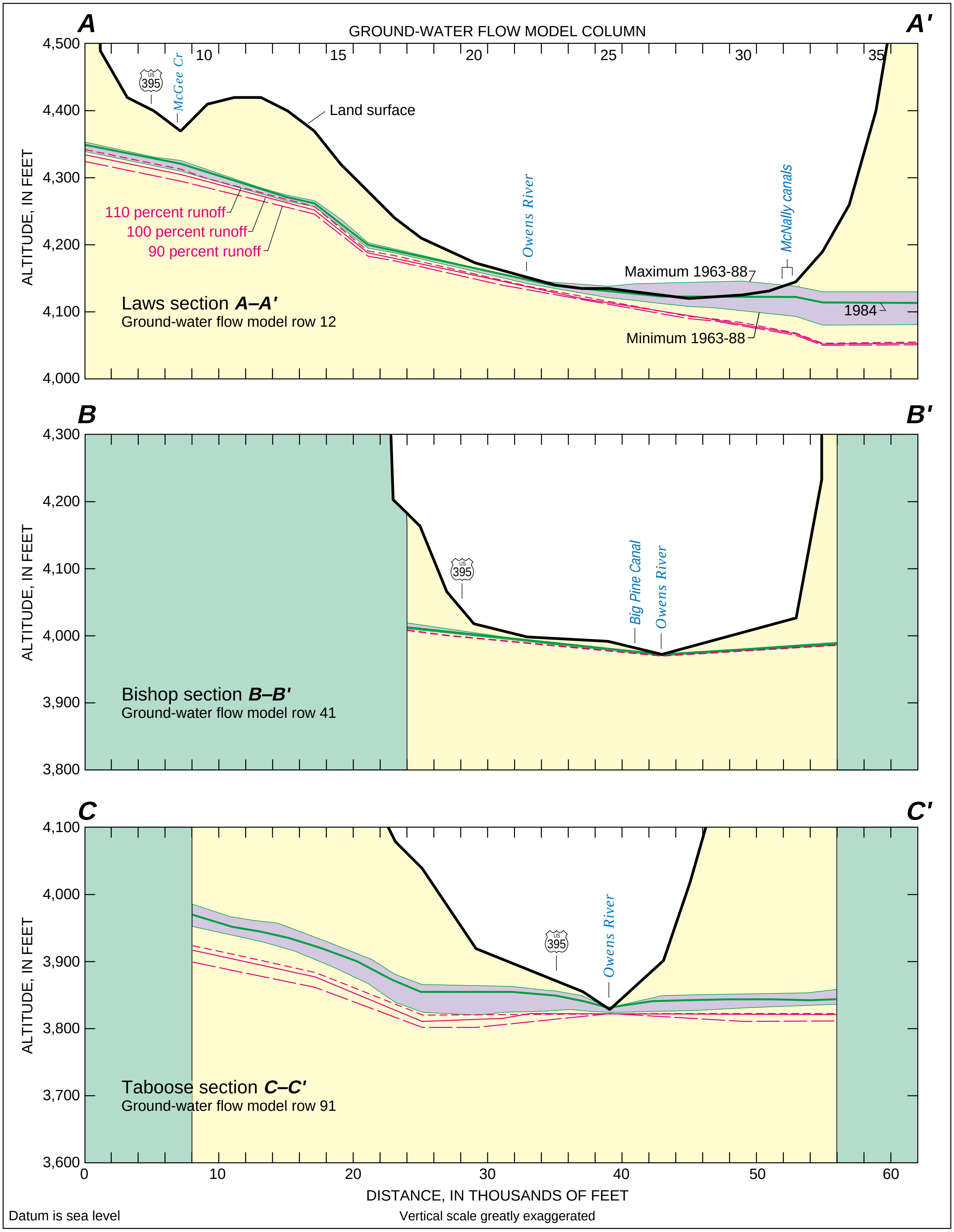

Figure 28. Sections showing the simulated water table in the Owens Valley, California, for 1998 steady-state conditions with different quantities of runoff. Line of sections shown in figure 26.

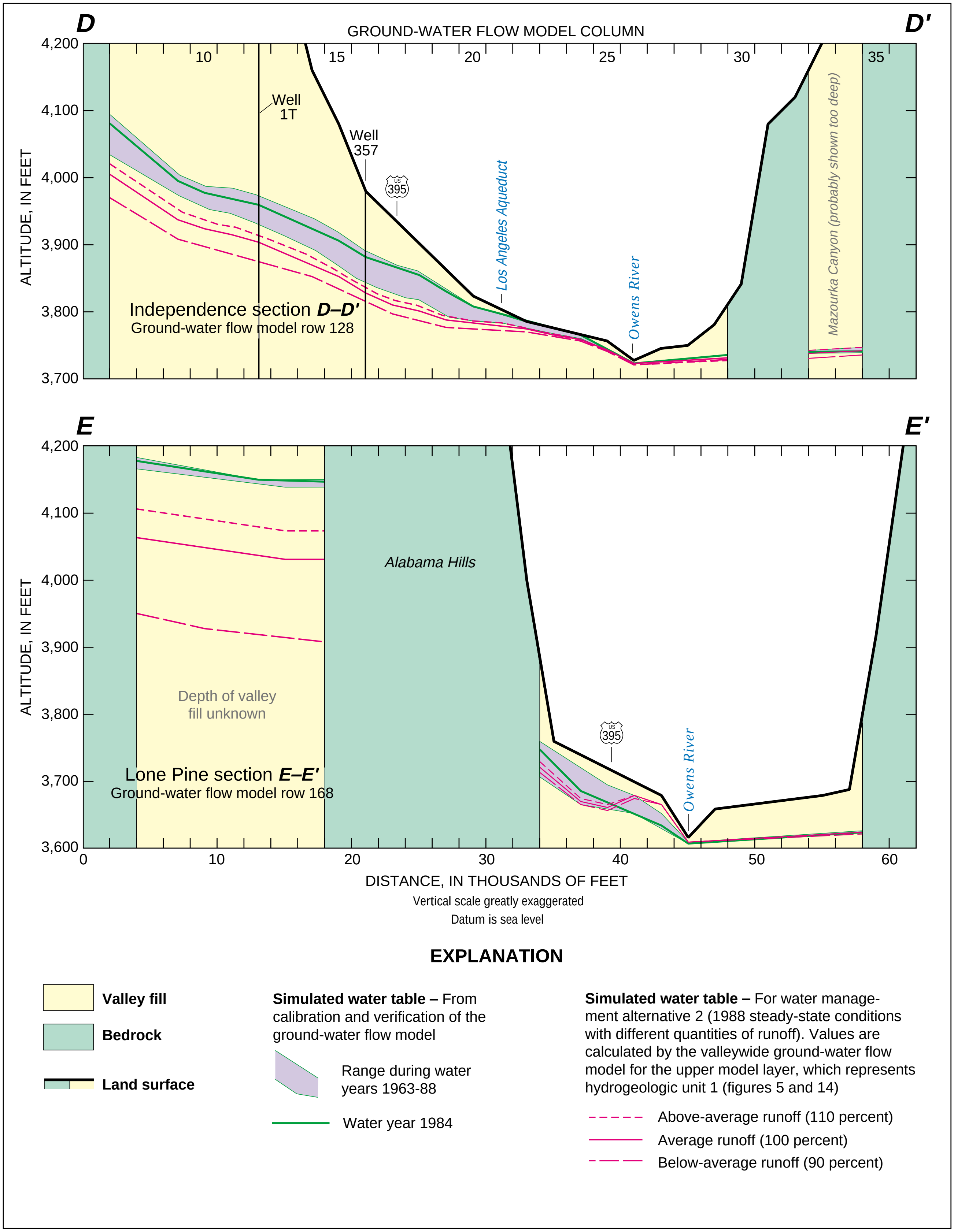

Figure 28. Continued.

recharge areas, particularly under the western alluvial fans. The river–aqueduct system, the lower Owens River, and native vegetation act as hydraulic buffers and help to reduce water-table changes near the valley floor.

Variations in runoff have less effect in the Bishop and the Laws areas than in the Taboose and the Independence areas. In the Lone Pine area, the marked change in the water table west of the Alabama Hills is largely a result of low transmissivities associated with the thin alluvial fan deposits and probably is not a major concern. The Alabama Hills effectively isolates the fan area to the west from the valley floor and related native vegetation to the east. In the Taboose and the Independence areas, however, the change in the water table beneath the alluvial fans translates to a significant decrease in the rate of ground-water movement toward the valley floor and a consequent decrease in evapotranspiration from the valley floor. Long-term monitoring of ground-water levels beneath the alluvial fans and valley floor and of evapotranspiration by native vegetation on the valley floor would identify such a long-term trend. In the Lone Pine area just west of the Owens River, the simulated water table for 1988 is higher than that for 1984 because of additional recharge from a new enhancement and mitigation project started in 1988.

Also of importance in figure 28 is a change in the river–aqueduct system in section *C–C′*. Simulation of 1988 steady-state conditions and variations in runoff of 10 percent indicate that under these conditions the river–aqueduct loses water to the Taboose–Aberdeen well field to the west. This change in flow direction could be verified with detailed water-level monitoring and water-quality sampling of the river–aqueduct and aquifer systems.

One management technique to minimize the effect of a long-term decrease in runoff is to increase the recharge from streams that have relatively low loss rates (fig. 13 and table 11). These streams include Bishop, Big Pine, Birch, Shepherd, and Lone Pine Creeks. Indeed, on the basis of results from alternative 1, increasing the recharge from streams is indicated even if long-term runoff does not decrease. Because past management efforts have pursued this option, it is unclear how much more water can be recharged on the alluvial fans in the critical areas of Taboose and Independence. An alternative management technique is to selectively decrease pumpage in sensitive areas.

The effects of a slightly different long-term average runoff, such as might occur as a result of climatic variations in precipitation, are less than those induced by human water-management decisions. Long-term variations in climate that produce slightly different annual quantities of runoff, assuming that stream-loss relations (fig. 13) continue to be valid, will not markedly affect the valley.

Alternative 3: Increase or Decrease Long-Term Average Pumpage

Alternative 3 addresses the question, “What will happen if average pumpage is increased or decreased from 1988 steady-state conditions?” One of the few aspects of the hydrologic system of the Owens Valley that can be altered readily is the quantity of pumpage. Over the past 20 years, pumpage has increased (fig. 17; tables 10 and 15) and has been the primary cause of change in the Owens Valley aquifer system during that time. Alternative 3 simulates scaling average annual basinwide pumpage up or down.

The design of alternative 3 was similar to that of alternative 2. Steady-state conditions for 1988 were assumed for all ground-water recharge and discharge, except pumpage. The value of pumpage at each well was scaled to 25, 50, 75, 100, and 125 percent of the 1988 steady-state value (table 9). The 100-percent pumpage simulation is identical to the 100-percent runoff simulation (alternative 2), which is identical to the 1988 steady-state simulation (alternative 1).

Although future pumpage in the valley is likely to be somewhat different from past pumpage because old wells occasionally are replaced with new wells, this difference is probably minimal for steady-state conditions, such as those simulated in alternative 3. Replacement wells usually are right next to the original well and are designed to extract water directly from hydrogeologic unit 3 (lower model layer) in order to delay the effects of pumpage on the water table. Given sufficient time, however, these effects will be transmitted to hydrogeologic unit 1 (upper model layer). The change in well design is recognized as an important management technique for shorter time periods, but it will become less valuable over time as the entire aquifer system equilibrates. Also, the valleywide ground-water flow model, as demonstrated during calibration, is relatively insensitive to withdrawing a greater percentage of pumpage from the lower layer.

Results from simulating alternative 3 are shown in figure 29 for the same sections shown in figure 28. The variations in pumpage are shown in 25-percent increments of the assumed 1988 steady-state pumpage. The increments are arbitrary, but they are within the confidence limits of the calibration model. Also shown is the simulated water table for water year 1984 in order to aid in correlating with figure 28 and plate 1.

As was true of figure 28, the most notable feature shown in figure 29 is the significant difference between the simulated water table for water year 1984 and that for 1988 steady-state conditions (100 percent pumpage) (fig. 26). This difference illustrates the large quantity of pumpage assumed for 1988 steady-state conditions—a quantity that combines average pumpage for export and new pumpage for enhancement and mitigation projects. In order to approximate the 1984 levels, average pumpage needs to be decreased significantly, to about 50 percent of the value assumed for the 1988 steady-state conditions, or to about 75,000 acre-ft/yr (fig. 29 and table 15).

The general linearity of pumpage effects is shown by an approximately even change in water-table altitude for each 25-percent increment. This feature is to be expected for a model using constant transmissivities and operating within the linear range of head-dependent recharge and discharge relations (table 13). A marked change in water-table altitude, however, is visible in the Taboose area (section *C–C′* in fig. 29) for the 125-percent increment. This result indicates that the simulated water table in the surrounding area has dropped below the zone of linearity of the head-dependent evapotranspiration and stream-recharge relations (refer to McDonald and Harbaugh, 1988, p. 10–3 and 6–9). When this occurs, the hydraulic buffering action is no longer effective, and the water table declines at a more rapid rate.

Different parts of the basin respond very differently to reductions in pumpage. The greatest change in the water table occurs near pumped wells, near bedrock boundaries, and away from head-dependent sources of recharge, such as the river–aqueduct system. As a result, a large change in the water table occurs on the west side of the valley, and relatively little change occurs on the east side of the valley across the Owens Valley Fault where there are few pumped wells (figs. 14 and 17). As noted in the discussion of alternative 2, wide variations in water-table altitude beneath the alluvial fans (such as those shown in section *D–D'* in fig. 28) do not affect overlying vegetation but do change the hydraulic gradient toward the discharge areas, and thereby decrease evapotranspiration rates for native vegetation some distance away on the valley floor.

Changes in the water table in the Bishop Basin occur mostly in the Laws area (section *A–A′* in fig. 29). Because head-dependent recharge along the eastern edge of the basin near Laws is minimal, no additional source of water is available except ground-water storage, and the simulated water table rises and falls dramatically with changes in pumpage. A similar response has been observed in measured ground-water levels (pl. 1). If some sources of recharge in the Laws area, such as the McNally Canals (figs. 11 and 29), act in a head-dependent way rather than as defined quantities of recharge as simulated in the model, then the use of head-dependent relations (table 13) to simulate these features will lessen the simulated fluctuations in the water table near Laws (fig. 29). Gaging of discharge in the canals and ditches, in addition to monitoring local ground-water levels, will aid in better defining these surface-water/ground-water relations.

The simulated water table in the area just south of Bishop is as unaffected by changes in pumpage as by changes in recharge (compare figs. 28 and 29). This lack of response results primarily because the area historically has had little recharge or pumpage, and, therefore, little was simulated in the model. A similarly static response was found in measured ground-water levels for well 335T (pl. 1) during water years 1963–88, a period of large variations in pumpage and recharge.

A decrease in evapotranspiration from the valley floor in the area south of Bishop may occur, however, even when the water table changes as little as 2 to 3 ft (Sorenson and others, 1991, p. G33). This decrease in evapotranspiration coincides with a decrease in the biomass of the native vegetation, as noted by Griepentrog and Groeneveld (1981, map 2) and by Sorenson and others (1991, fig. 24). Therefore, caution is required in interpreting simulation results even in areas that appear to have a minimal change in water-table altitude.

In the Owens Lake Basin, the primary effects of simulated changes in pumpage occur between Taboose and Independence Creeks (fig. 29). There is an

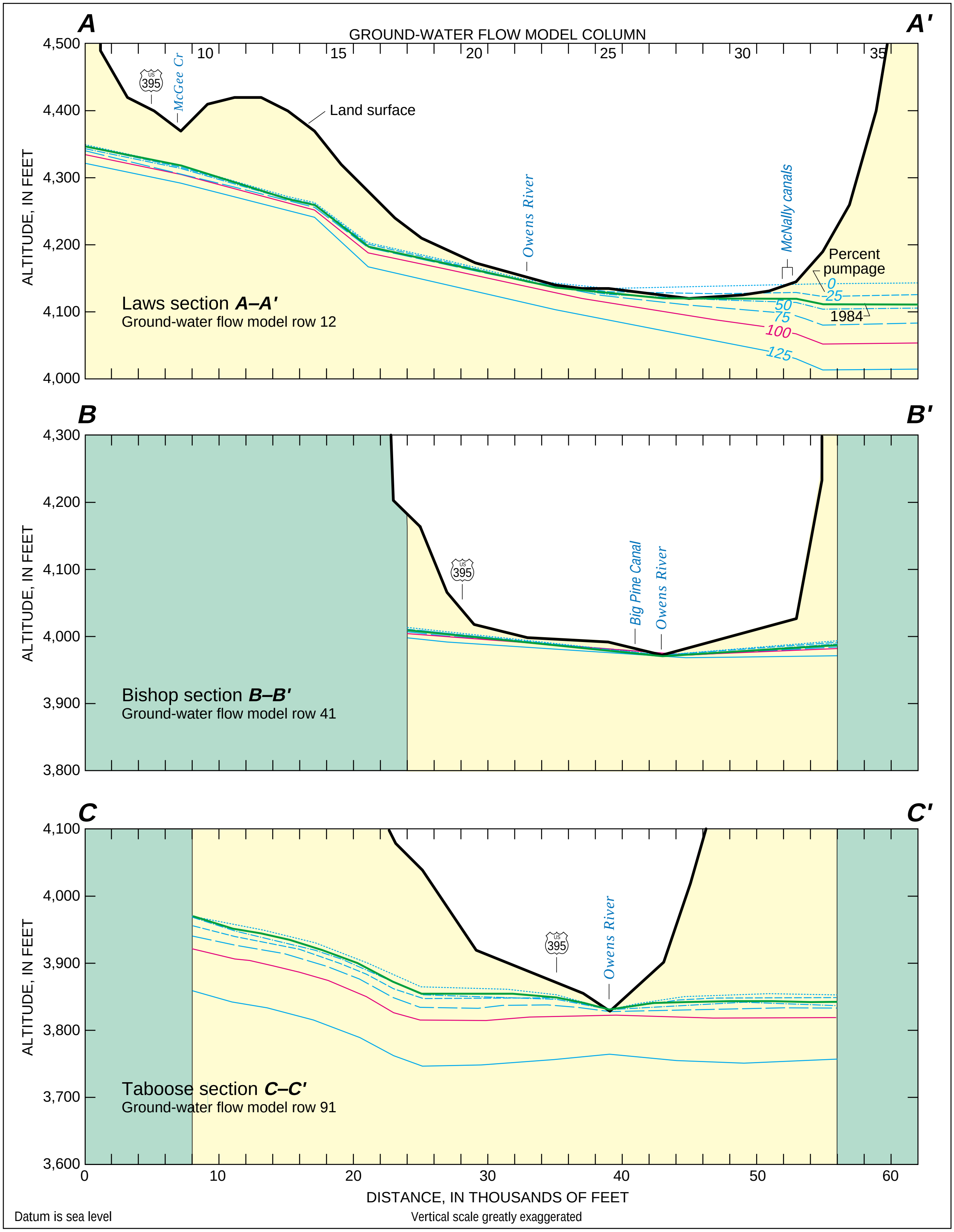

Figure 29. Sections showing the simulated water table in the Owens Valley, California, for 1988 steady-state conditions with different quantities of pumpage. Line of sections shown in figure 26.

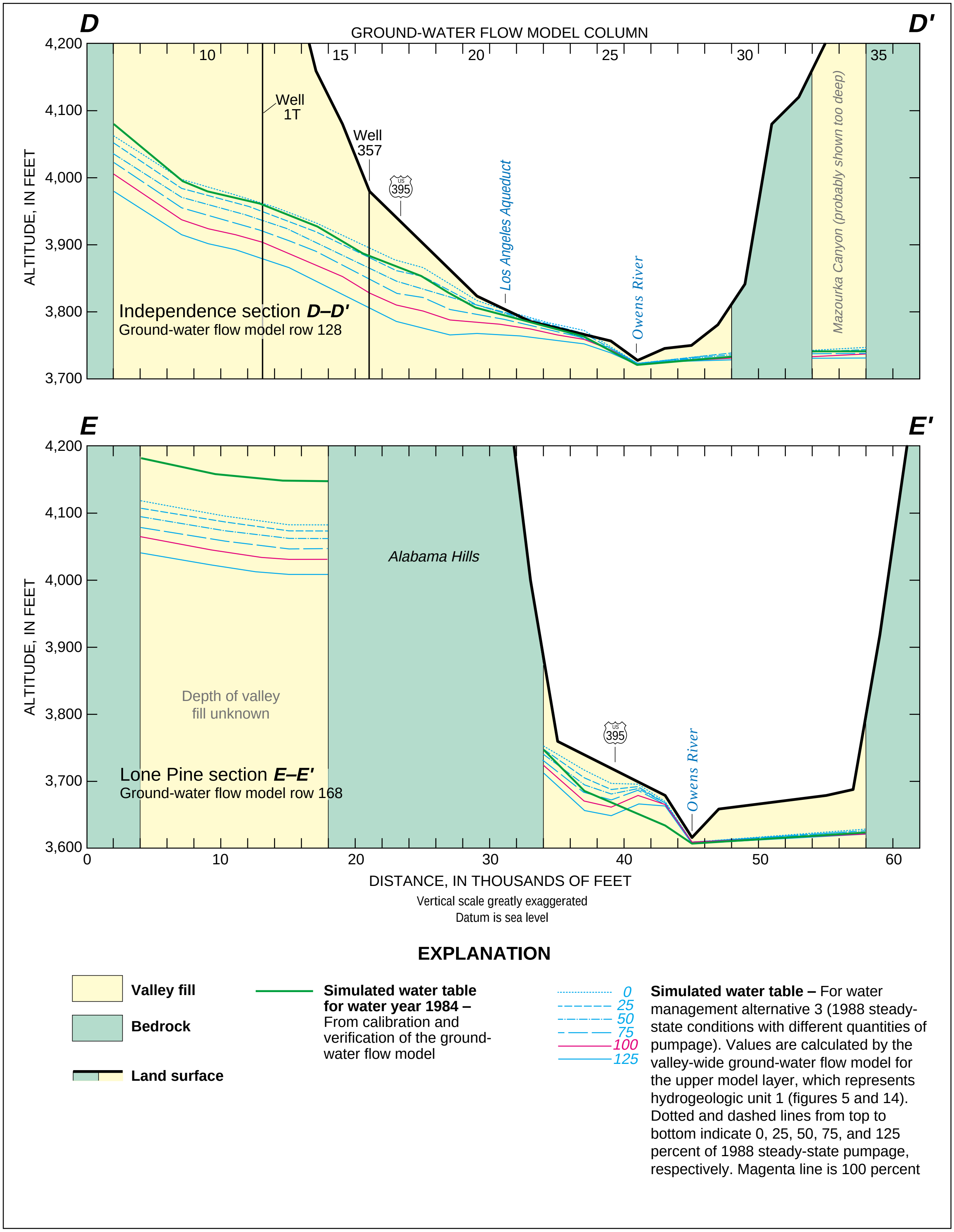

Figure 29. Continued.

indication in the Taboose area, as well as in the Laws area (section *A–A′* in fig. 29), that pumpage in excess of the 1988 steady-state quantity may cause hydraulic separation of the Owens River from the adjacent water table, creating a partially saturated zone beneath the river. This separation as simulated in the model causes a precipitous lowering of the water table, as discussed previously and as shown by the 125-percent increment.

In summary, results of model simulations suggest that the water table will continue to decline for some time if recharge and pumpage remain at the assumed 1988 steady-state values. This water-table decline will result in a decrease in evapotranspiration and a decrease in the biomass of native vegetation. Results of simulations indicate that to maintain the water table at an altitude similar to that of 1984, total pumpage needs to be about 75,000 acre-ft/yr, or about 50 percent of the assumed 1988 steady-state value.

Alternative 4: Manage Periodic Variations in Runoff and Pumpage

Alternative 4 addresses the question, “How can a sequence of dry and wet years be managed?” For example, which areas of the valley are likely to be affected most by a severe drought, which least, and how fast do the different areas recover? Which areas need help in recovering to pre-drought conditions? The Owens Valley hydrologic system historically has cycled between droughts and periods of abundant water (table 7). Because of the multiplicity of and constant change in water-management operations, such as during water years 1970–88, it is difficult to identify the effects of a typical cycle using historical data. Simulation of alternative 4 attempts to clarify these effects with a simple, but typical, management scenario.

A schematic of the 9-year transient simulation used for alternative 4 is shown in figure 30. The 9-year simulation period has similarities to drought, average-runoff, and above-average-runoff conditions experienced during the 1970's and 80's. Initial conditions for alternative 4 were assumed to be alternative 1 (1988 steady-state) conditions. The first 3-year period (I) represents drought conditions and simulates 70 percent of average runoff and maximum pumpage. Maximum pumpage is defined as the maximum annual pumpage recorded at each well during water years 1985–88; maximum pumpage for enhancement and mitigation wells is the value recorded for water year 1988 (table 11). The implicit water-management goal during the first 3-year period is to maximize export of ground water to compensate for decreased export of surface water. The second 3-year simulation period (II) represents a return to average conditions and simulates 100 percent of average runoff and the same value of pumpage as the initial (1988 steady-state) conditions. The management question during the second period is, “How fast does the system return to normal?” The third 3-year simulation period (III) represents wet conditions and simulates 130 percent of average runoff and the same average pumpage as during the second 3-year period. Actual pumpage during a wet cycle most likely will be somewhat less than average, particularly after a couple of wet years (fig. 18). This decrease, however, is poorly quantified for future conditions and was not incorporated in the simulation. Results from the third period identify areas of the valley in which the simulated heads have not recovered to initial conditions even after 3 years of average conditions and 3 years of wet conditions. Specific values of recharge and discharge are given in table 11.

The simulated change in water-table altitude at the end of each 3-year period (drought, average, and wet) with respect to initial conditions is shown in figures 31, 32, and 33, respectively. Because no site-specific water-management techniques were incorporated in the simulation, the results identify those stressed areas of the valley that require additional monitoring and possibly additional manipulations of ground-water recharge and discharge.

The areas of the valley that show the greatest effects at the end of a 3-year drought marked by lesser runoff and greater pumpage are identified in figure 31. Clearly, the effect of drought is widespread. Much of the decline in the water table occurs beneath the alluvial fans and volcanic deposits, as in other simulations (figs. 23, 26, 28, and 29). Areas with the most dramatic changes are those in abundant recharge areas (Bishop and Oak Creeks). Other areas with significant water-table decline are near the well fields (Laws, Big Pine, Taboose–Aberdeen, and Independence–Oak) (fig. 17). As determined during sensitivity analysis of the ground-water flow model, the effect of lower runoff near well fields is minimal in comparison with the effect of nearby pumping.

Some areas on the valley floor that have a simulated decline in water-table altitude greater than 10 ft are areas that are covered with native vegetation identified as susceptible to stress from pumping (R.H. Rawson, Los Angeles Department of Water and Power, written commun., 1988; Sorenson and others, 1991). The significant water-table decline in these areas decreases evapotranspiration, prompts native vegetation to drop leaves, and reduces total biomass on the valley floor. Some species, such as rabbitbrush

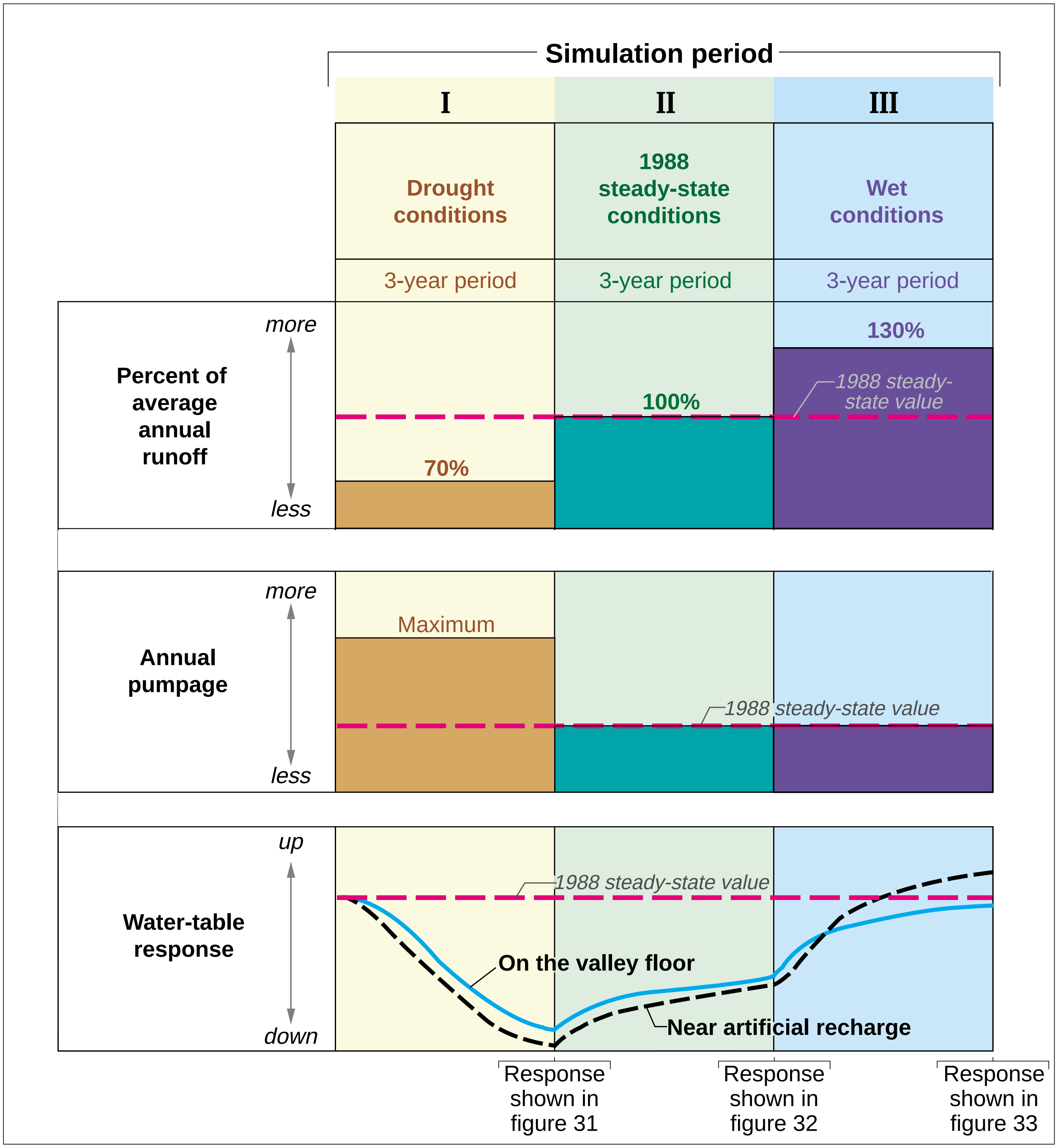

Figure 30. Diagram of water-management alternative 4 for the Owens Valley, California. Shown are changes in percent of average annual runoff, annual pumpage, and water-table response at typical locations in the valley during the 9-year simulation period. Results at the end of each 3-year period are displayed in figures 31–33.

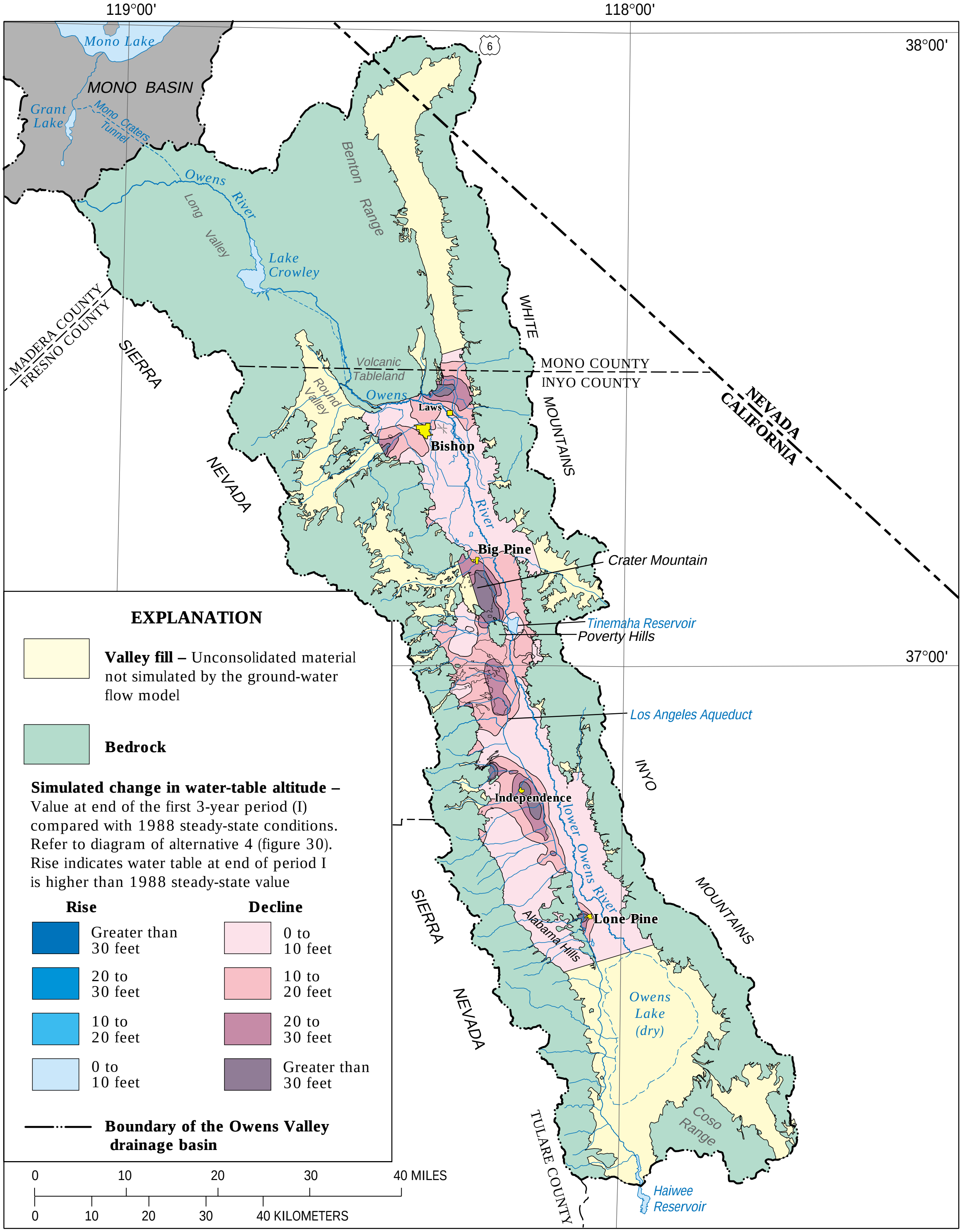

Figure 31. Simulated change in water-table altitude in the Owens Valley, California, for water-management alternative 4 at the end of period I, representing 3 years of drought.

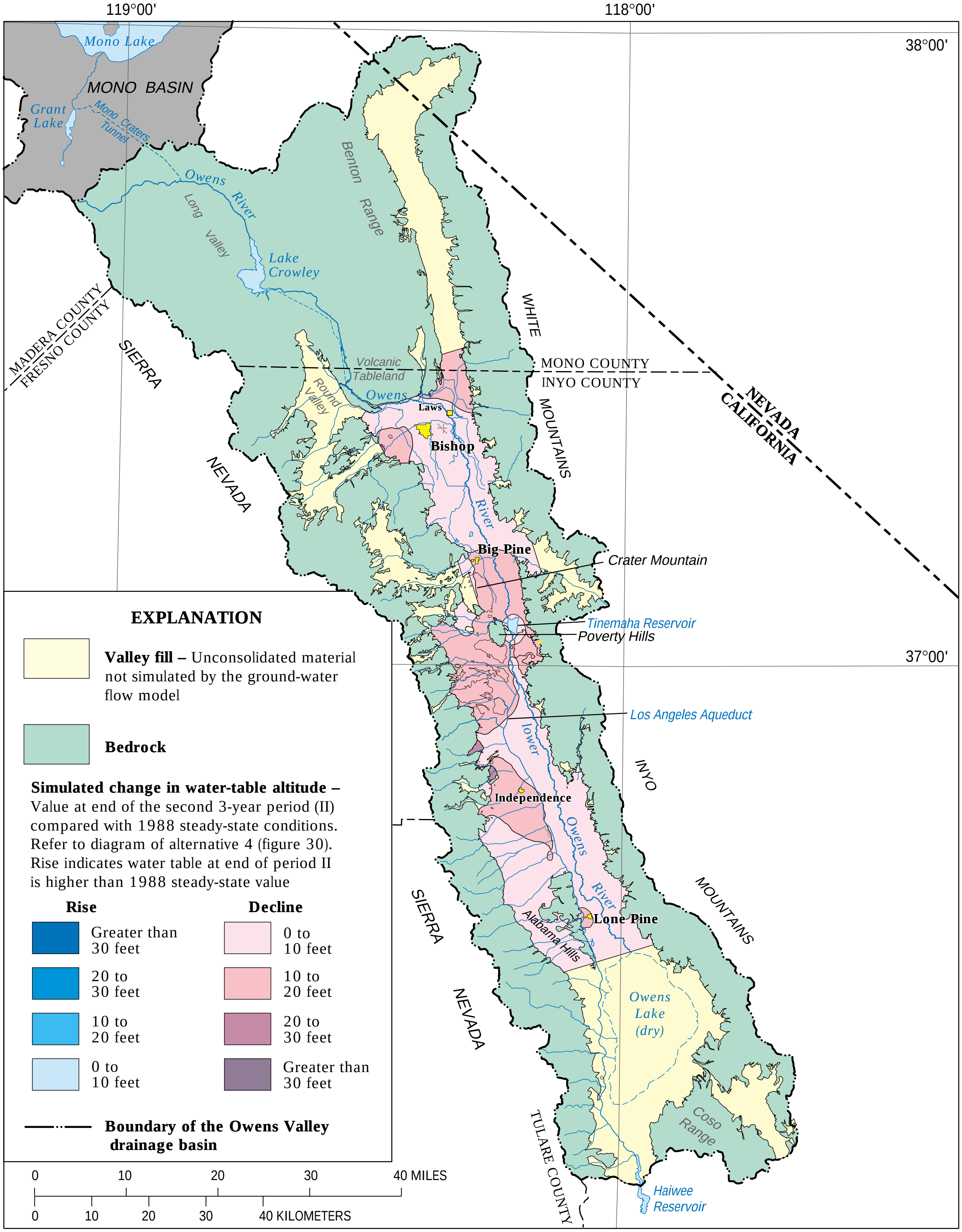

Figure 32. Simulated change in water-table altitude in the Owens Valley, California, for water-management alternative 4 at the end of period II, representing 3 years of recovery.

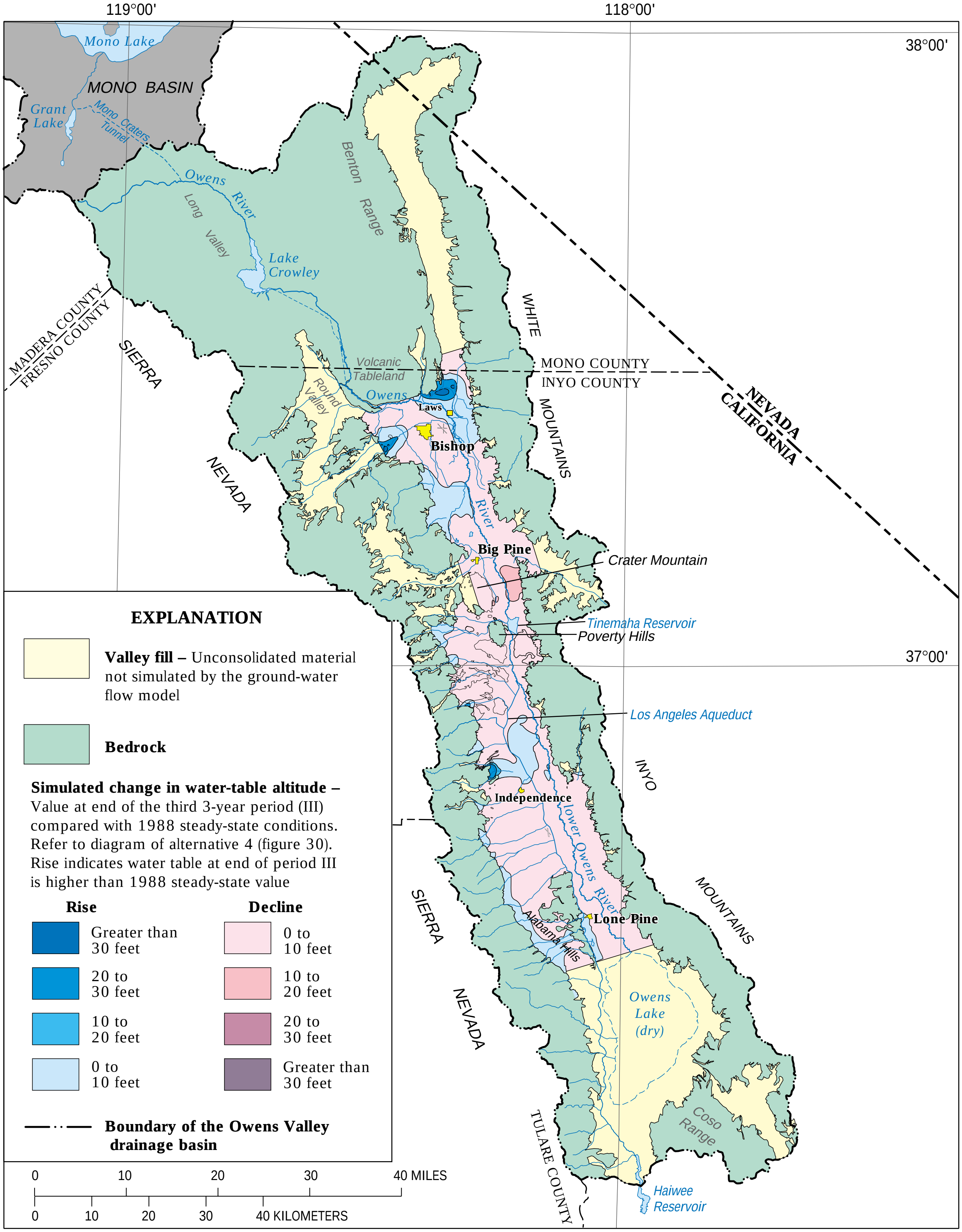

Figure 33. Simulated change in water-table altitude in the Owens Valley, California, for water-management alternative 4 at the end of period III, representing 3 years of wet conditions.

(Sorenson and others, 1991, p. G35) may die during a 3-year drought if the plants cannot grow additional roots deep enough and fast enough.

Areas of the valley floor that are isolated from recharge and pumping effects, such as between Bishop and Big Pine and east of the Owens River, have a simulated decline in water-table altitude of only a foot or two. Although some decrease in evapotranspiration is likely, the effects on native vegetation are much less than effects near recharge areas and well fields. Because these isolated areas have few monitoring wells, simulation results need to be viewed cautiously.

The Taboose–Aberdeen area exhibits a broad areal change in water-table altitude, broader than in most other areas of the valley. The many springs in the area historically acted as hydraulic buffers and dampened the effects of pumping on water-table fluctuations. That capacity, however, now is largely gone (figs. 17 and 21), and, with changes in pumpage, the water-table fluctuations are greater (pl. 1). Neither the Owens Valley Fault nor the unnamed fault near the aqueduct (fig. 14) is an effective barrier to ground-water flow in this part of the Owens Lake Basin. Cones of depression in the water table created by pumping in well fields (fig. 17) propagate unimpeded eastward across the valley.

In the southern part of the Bishop Basin, cones of depression are transmitted even more effectively through hydrogeologic unit 3 to the east side of the valley because of the presence of the relatively impermeable blue-green clay (Hollett and others, 1991, pl. 1). This thick clay layer effectively restricts the vertical flow of water from hydrogeologic unit 1 to hydrogeologic unit 3 in the center of the valley. Release of water from hydrogeologic unit 3 is derived mostly from elastic expansion of water and compression of the aquifer, which results in a storage coefficient that is much smaller than specific yield. As a result of these conditions, the cone of depression expands to cover a large area. The highly transmissive sand and gravel beds in hydrogeologic unit 3 aid in propagating the cone of depression horizontally. On the east side of the valley, the alluvial fan deposits have a greater vertical hydraulic conductivity than does the blue-green clay, and ground water can readily flow from hydrogeologic unit 1 to hydrogeologic unit 3. In this way, the water table along the east side of the valley responds to pumping on the west side. The net result is that most of the nearby area north and south of the Tinemaha Reservoir exhibits a significant decline in the simulated water table. Associated adverse effects on nearby native vegetation are likely, particularly in areas distant from surface-water features, which are a source of recharge.

Historical water-management operations in the Owens Valley have tended to create feast or famine conditions for native vegetation. For example, the recent (1984) rise in the water table near Laws and Independence (fig. 23) resulted from an abundance of recharge in these areas, primarily as a result of water-spreading activities by the Los Angeles Department of Water and Power (pls. 1 and 3; table 11), and from a temporary reduction in pumpage (fig. 17). Native vegetation responds to increased water availability by increasing leaf growth or plant density, which results in a commensurate increase in evapotranspiration (Groeneveld and others, 1987). A subsequent period of drought and increased pumpage, such as during water years 1987–88 (pl. 1) or as simulated during the first 3-year period of alternative 4 (figs. 30 and 31), results in a declining water table and a decrease in plant leaf area and evapotranspiration. The declining water table then prompts a water-management decision to decrease pumpage and implement water-spreading efforts to increase recharge when water is again abundant. This cyclic pattern of response by the aquifer system and native vegetation to alternating drought and high runoff, accentuated by water-management decisions that increase pumpage during droughts and then increase artificial recharge during periods of high runoff, typifies a more highly managed Owens Valley.

One attribute of a more highly managed aquifer system is that native vegetation will be less evenly distributed. The natural flow of the aquifer system tends to smooth out ground-water levels, recharge, and discharge. Human changes in the aquifer system tend to focus recharge and discharge into smaller areas. As the valley becomes more controlled, 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, native vegetation will be using less water than it had been using prior to the increase in water development.

A water-management goal for most ground-water basins is the same as for a surface-water reservoir. Empty the reservoir when water is scarce; fill it when water is plentiful. The paradox in managing the Owens Valley is that if the water table beneath the valley floor fluctuates too much, native vegetation is adversely affected. Therefore, the reservoir must be kept virtually full.

Alternative water-management techniques to lessen the effect of pumping on the water table and nearby native vegetation are limited in many ways, as discussed in the section "General Water-Management Considerations." From a long-term, valleywide perspective, the water table is affected most by the quantity of water pumped, not by the particular location of pumping in the valley (fig. 26). Nevertheless, locations with pumped wells have greater fluctuations in the water table and a greater likelihood of having native vegetation adversely affected by water-table fluctuations (compare figs. 17 and 31). Locating pumping on alluvial fans away from the valley floor will lessen the decline of the water table near sensitive vegetation. Pumping from high on the western alluvial fans, in particular in areas of abundant recharge, will lessen the immediate effects on the valley floor.

However, past experiences of drilling on the western alluvial fans (well 1T, pl. 1) showed that installation of wells has been difficult or nearly impossible because of massive rock and boulders (M.L. Blevins, Los Angeles Department of Water and Power, oral commun., 1987). Also, transmissivities of the alluvial fans and related well yields are significantly less than in transition-zone or volcanic deposits (fig. 15). Electrical usage is higher in order to lift water the greater distance to land surface. Similar difficulties might be encountered in installing new wells on the eastern alluvial fans. In addition, the eastern alluvial fans are areas of limited recharge and, possibly, poorer quality ground water with a higher concentration of dissolved solids.

Pumping from high on the Bishop Creek alluvial fan (Bishop Cone), although now limited by the Hillside Decree, probably would produce minimal effects on the valley floor, especially if pumping were limited to short-term supply during a drought. This broad, gently sloping fan is characterized by abundant recharge from Bishop Creek. The fan has additional recharge potential through the use of spreading basins, and it might be easier to drill through this fan than through the steep, rocky fans near Independence.

Much of the valley floor in the Bishop and Big Pine areas is urban or irrigated land that is not affected by a decline in the water table. Additional pumping from within these areas probably will have less effect on native vegetation than pumping from other areas of the valley floor.

Pumping only from lower zones of the aquifer system, beneath hydrogeologic unit 1, reduces the immediate decline of the water table. The amount of this reduction is unknown, but it could be approximated using detailed, site-specific ground-water flow models of individual well fields, or possibly by field testing a single pumped well surrounded by several, multiple-depth monitoring wells (Driscoll, 1986, p. 719–728). The benefit of pumping from lower zones, however, decreases the longer the wells are pumped continuously. Hydrogeologic boundary conditions and vertical leakage through hydrogeologic unit 2 and alluvial fan deposits eventually will transmit the effects of pumping from lower zones to hydrogeologic unit 1, lowering the water table and decreasing evapotranspiration from areas where the water table is within 15 ft of land surface (table 5).

Differences in the simulated water-table altitude following 3 years of drought and 3 years of average conditions are shown in figure 32. The areas of residual decline in the water table are similar to those in figure 31, but the magnitude is less. Areas where the decline is greater than 10 ft indicate locations in the valley that need careful monitoring of the water table, soil-moisture zone, and native vegetation. Results from simulating alternative 4 also suggest that monitoring the effects of a drought need to be continued for several years following the end of the drought—much longer than previously thought necessary.

Differences in the simulated water-table altitude following 3 years of drought, 3 years of average conditions, and 3 years of 130-percent runoff are shown in figure 33. As expected, recharge areas show a considerable rise in the water table, as do areas of focused artificial recharge, such as near Laws and Independence (fig. 33 and pl. 3). Somewhat surprising, however, is that 6 years after a drought and immediately following 3 years of above-average runoff, the water table in many areas of the valley still shows signs of the drought and coincident pumpage. Minor residual drawdown is present over most of the valley floor, and an isolated area of declines greater than 10 ft still is present beneath the alluvial fans east of Big Pine. This result demonstrates the slowness of recovery in areas away from abundant recharge.

The period of recovery for the water table is much longer than was hypothesized at the beginning of the modeling studies. This characteristic of the aquifer system, however, agrees well with the tentative conclusion that the aquifer system and native vegetation were still in transition in the mid-1980's from the effects of increased pumping in the early 1970's and the drought conditions in 1976–77.

The water-table decline simulated in alternative 4 can be reduced by focusing artificial-recharge efforts in areas of greatest decline and concentrated pumping (figs. 17 and 31). Localized recharge efforts may need to be continued for as long as 6 years after the end of a 3-year drought in order to compensate for the decline in water table. Areas of abundant water and lush vegetation induced by artificial recharge likely will become areas of stressed vegetation in future drought conditions (compare figs. 31 and 33).

Because of the limitations associated with the valleywide ground-water flow model and the unique characteristics of a particular drought, ongoing monitoring of the aquifer system, soil-moisture zone, and native vegetation needs to be continued, particularly in areas simulated in alternative 4 as having water-table declines greater than 10 ft (figs. 31, 32, and 33).

Optimal Operation of Well Fields

An extensive body of literature deals with the general topic of mathematical optimization of physical systems (Gorelick, 1983; Rogers and Fiering, 1986), and a few applications have been made to combined surface-water and ground-water systems (Young and Bredehoeft, 1972; Bredehoeft and Young, 1970, 1983; Danskin and Gorelick, 1985). Although use of these techniques was proposed initially as a promising method of evaluating water management in the Owens Valley, detailed appraisals during the 6-year study identified several numerical limitations. The mathematical dimensions ($m \times n$ matrix) required by a realistic optimization model for the Owens Valley are very large. There are more than 40 streams, 9 well fields, 200 production wells, 800 observation wells, and 600 surface-water gaging stations—as well as a multitude of decision points in the basin, such as whether or not to divert a stream. Also, the optimization problem is moderately nonlinear as a result of the piecewise-linear relations used to approximate some recharge and discharge components in the ground-water flow model (table 13). The large dimensionality and nonlinearities would require considerable computer time to solve even a relatively simple problem in a mathematically rigorous way. As computer capabilities increase and costs diminish, a basinwide optimization study may prove to be more tractable. The approach presented in this report uses the basics of the mathematical optimization techniques and could serve as the foundation of a simple optimization model.

The actual operation of individual well fields is a complex and iterative process, dependent on many factors—including those general concerns presented in the section entitled “General Water-Management Considerations,” as well as day-to-day concerns of mechanical efficiency, repair and maintenance, and personnel requirements. Optimal operation probably involves meeting several different objectives, which makes the mathematical problem even more complex and makes a simple, instructive version of the water-management system difficult to define.

For this evaluation, however, optimal operation of well fields was defined in a semi-quantitative way to be the most pumpage for the least adverse effect on native vegetation. The ground-water flow model was used to determine the effect of pumpage from each well field. The model response, referred to in optimization literature as a “response function,” is the change in head, recharge, and discharge in response to a defined increase in pumpage. A unit increase in pumpage produces a “unit response.” Those well fields that produce the least adverse effects on native vegetation (least water-table decline under vegetation that relies on ground water) are considered the optimal well fields to use. Well fields with a greater water-table decline are less desirable, or less optimal.

Two similar analyses were done to determine the effect of pumpage from each well field. Each analysis involved simulating the response to pumpage at individual well fields. The simulation timeframe was 1 year with constant stresses. Initial conditions for each simulation were the 1988 steady-state conditions (alternative 1). To simplify the analysis, the Independence–Oak, the Symmes–Shepherd, and the Bairs–George well fields (fig. 17) were grouped together and are referred to as the “Independence south” well field. The Lone Pine well field was not included in the first analysis because of its limited capacity, the presence near the well field of relatively fine-grained and less transmissive aquifer materials (figs. 15 and 16), and the abundance of nearby en echelon faults that limit production (fig. 4).

The first analysis involved increasing pumpage at each well field (tables 11 and 15) by 10,000 acre-ft/yr more than the 1988 steady-state simulation (alternative 1). Pumpage for an individual well was increased in proportion to its 1988 steady-state value (table 11). After 1 year of simulation, the decline in water-table altitude was noted and is shown in figure 34. From this analysis, the well field having the greatest effect on native vegetation is readily discernible as the one producing the greatest water-table decline under the largest area of native vegetation