4.0 ANALYSIS OF PUMPING

Following calibration and sensitivity analyses the model was used for future predictions of the potential impacts of 40 years of plant pumping at the maximum annual pumping rate of 3,000 gpm (4,850 ac-ft/yr). The locations of the pumping wells are shown on Figure 33. Each of the model runs described below is the result of three model calculations: a steady state (non-pumping) case to provide initial conditions, a transient model run with pumping, and a transient model run without pumping. The non-pumping results were subtracted from the pumping results in order to arrive at predicted changes due solely to pumping and to remove any model-generated errors over the course of 100 and, in one case, 200 years of transient calculations.

4.1 PREDICTED DRAWDOWNS

The results for the base case are shown on Figures 34 through 36a. The predicted drawdowns in the volcanic (lower) aquifer show an almost uniform drop in water levels of about 85 ft. In the middle aquifer (Figure 33), a general zone of small drawdowns (less than 4 ft) is predicted as a result of 40 years of pumping. This zone is centered above the pumping area and extends outward in areas where the lakebed clay thins. In the upper aquifer (Figure 36), a small zone of less than 0.5 ft predicted drawdown is shown after 40 years of pumping. In summary, a base-case model using a specific yield of 11 percent shows that predicted drawdowns as a result of 40 years of pumping range from less than 0.5 ft (upper aquifer) to less than 4 ft (middle aquifer) to 85 ft (volcanic aquifer). The predicted area of maximum potential drawdown in the upper aquifer is in the vicinity of the Denton well and Banegas Ranch well No. 2. This is the section of river where the lakebed clay is mapped by USGS as being absent. The predicted effects on river flow and river underflow are discussed in Section 4.2.

The sensitivity cases were also used to predict an envelope of potential predicted impacts. The worst realistic case was the 4×10^{-5} ft/d aquitard conductivity case with higher rates of recharge to the volcanic aquifer, because this case leads to the greatest predicted drawdowns in the upper and middle aquifers. Volcanic, middle, and upper aquifer predicted drawdowns for this case are shown on Figures 37 through 39. A drawdown of less than 1 ft in the upper aquifer is predicted in this high aquitard conductivity case. It should be noted that high recharge rates (2.7 times the average rate) were applied in this case in order to maintain the observed vertical head gradients between aquifers.

The best feasible case was the 1×10^{-6} ft/d aquitard conductivity case, because this case leads to the least predicted drawdowns in all aquifers. The predicted groundwater level drawdown from the project in this case was approximately 65 ft in the lower (volcanic) aquifer, less than 0.5 ft in the middle aquifer, and less than 0.1 ft in the upper aquifer.

Predicted drawdowns over time for the base and sensitivity cases are shown on Figures 40 through 42. The most sensitive parameter tested is aquitard conductivity. Potential impacts of less than 1 ft drawdown in the upper aquifer are predicted to occur after 20 or 30 years of pumping. The volcanic aquifer is predicted to take about 130 years for 90 percent recovery to pre-pumping heads.

4.2 PREDICTED FLOW RATES INTO THE RIVER ALLUVIUM

Groundwater flow rates to the river alluvium were predicted for the base and sensitivity cases. It was predicted that drops in flows to the marsh, gorge and, to a small degree, to evapotranspiration outside the marsh, due to project pumping, would occur (refer to Table 9). The potential decrease in flows is predicted to occur gradually over the period of pumping. Both the response and recovery times were predicted to be very slow.

TABLE 9
PREDICTED FLOW RATES IN THE RIVER ALLUVIUM[a]
AT YEAR 40

Flow Rates	Base Case		RealisticWorst Case: Aquitard conductivity of 4x10^{-5} ft/d		Less Evaporative Marsh		7% specific yield case		15% specific yield case		Best Case: Aquitard conductivity of 1x10^{-6} ft/d	
	(gpm)	(ac-ft/yr)	(gpm)	(ac-ft/yr)	(gpm)	(ac-ft/yr)	(gpm)	(ac-ft/yr)	(gpm)	(ac-ft/yr)	(gpm)	(ac-ft/yr)
Underflow Through Gorge (Davidson, 1973)	496	800			496	800						
Flow Rate in Big Sandy River 1 mile downstream of Gorge (BLM measurement)	2,034	3,280			2,034	3,280						
Rate of Evaporation, and Evapotranspiration at Marsh (Table 1)	1,893	3,053			1,893	3,053						
Predicted Groundwater Flow Rate under Non-Pumping Conditions												
Flow Rate into Marsh	5,733	9,247	6,175	9,960	1,311	2,115	5,734	9,248	5,732	9,245	5,139	8,289
Flow Rate Through Granite Gorge	965	1,556	997	1,608	2,208	3,561	965	1,557	965	1,557	922	1,487
Flow Rate to Evapotranspiration	8,795	14,185	8,732	14,084	8,660	13,968	8,795	14,185	8,796	14,187	8,258	13,319
Predicted Groundwater Flow Rate After 40 years of Pumping												
Flow Rate into Marsh	5,600	9,032	5,901	9,518	1,258	2,029	5,543	8,940	5,629	9,079	5,134	8,280
Flow Rate Through Granite Gorge	954	1,539	976	1,574	2,152	3,471	949	1,531	956	1,542	922	1,486
Flow Rate to Evapotranspiration	8,785	14,169	8,711	14,050	8,635	13,927	8,781	14,163	8,787	14,172	8,256	13,316
Combined Change in Flow Rate to Marsh, to Evapotranspiration, and Through Gorge	155	248	317	510	135	217	222	356	122	196	8	13

[a] Storativity of 1 x 10^{-6} ft^{-1} used in all cases.

It was concluded from these results that:

- the base case and less-evaporative marsh cases bracket the (imprecise) data for outflows from the Big Sandy basin at the south end of the valley.

- alternate marsh scenarios predict a redistribution of flows between the gorge and the marsh, but do not significantly change the predicted overall drop in flow rates in the southern end of the valley

The overall predicted drop in flow rates to the river alluvium includes drops in evapotranspiration, drops in flow to the marsh, and drops in outflow through the gorge. These predicted drops in flow vary from zero to a maximum as a result of 40 years of pumping, as shown in Table 10. For the worst realistic case, overall groundwater flow to the alluvium flow is predicted to drop by up to 1 percent (371 gpm or 598 ac-ft/yr) by year 70.

TABLE 10
PREDICTED DROP IN FLOW RATES TO THE RIVER ALLUVIUM OVER TIME

Time Since Pumping Began (Years)	Predicted Drop in Flow Rate to River Alluvium			
	Base Case		Realistic Worst Case: Aquitard conductivity of $4x10^{-5}$ ft/d	
	(gpm)	(ac-ft/yr)	(gpm)	(ac-ft/yr)
0	0	0	0	0
10	32	52	60	97
20	72	116	145	234
30	112	181	230	371
40 (pumping stops)	155	248	317	510
50	168	271	350	564
60	170	274	365	589
70	166	268	371	598
80	161	260	371	598
90	155	250	371	598
100	151	244	371	598

5.0 ANALYSIS OF WATER REPLACEMENT

As discussed in Section 4.2, decreases in inflow to the river alluvium due to pumping of the lower aquifer are predicted for the base and sensitivity cases. These predicted decreases in inflow were calculated using the zone budget feature in MODFLOW to estimate the inflow under the pumping and non-pumping scenarios and comparing these two values. Subsequently, model runs were used to evaluate the potential for replacement of the decreases in inflow to the river alluvium by both subsurface injection of water and augmentation of surface water.

The steady state base case of the model was used to test the potential locations for either injection of water into the groundwater system or augmentation of the surface water flows in the system. Several model simulations were performed including the assessment of the injection of water at:

- the location of monitor well OW1,
- the location of monitor well OW8,
- the southern end of the Banegas Ranch, and
- at all three of the above locations.

The model simulations performed indicated that injected water in the areas of wells OW1 and OW8 using small volumes of water could offset the predicted drawdowns upstream of the marsh. As these simulations were developed, the location near the southern end of the Banegas Ranch was incorporated to attempt to offset the drawdowns in the southern end of the Big Sandy Basin. Subsequent runs were performed at varying injection rates, which indicated that the marsh (simulated as a general head boundary) was the principal area of water loss in the Big Sandy River alluvium due to pumping from the lower aquifer. Further analyses of the zone budget from the marsh area indicated that the principal reduction in outflow from the basin was the result of reduction of evapotranspiration and evaporation from the marsh and the translation of this reduction into drawdown.

As a result of the realization that the marsh is the principal mechanism for the reduction in outflow of water from the Big Sandy River alluvium, subsequent model runs focused on the potential for balancing the decreased losses by evapotranspiration and evaporation (and thus the drawdowns) with augmentation of water into the marsh area. To simulate this potential offset, the general head boundary within the model was redefined as a series of wells. The simulation of the marsh as a series of wells allows fluxes from the marsh to be specified. The specified flux initially simulated was determined by total flow out of the marsh during the non-pumping scenario. To this value, the predicted amount of decrease in inflow to the river alluvium was added in a time-varying fashion, thus providing a method of simulating the augmentation to the marsh.

Several model runs were performed that simulated variations on the water augmentation scenario. These model runs indicated that the predicted drawdowns are very sensitive to the total flux value out of the marsh. Eventually, simulations were achieved that resulted in both a drawdown of less than 0.5 feet and a mounding of less than 0.5 feet. These simulations were achieved with a change in flux of less than 60 gallons per minute (gpm). Both the mounding and the drawdown simulations indicate that the offset program via augmentation to the marsh is viable, and provides a mechanism and location where decreases in inflow and head in the river alluvium due to pumping may be entirely offset.

If water is placed into the marsh over the lifetime of the project, it is likely that this will act to reduce the reduction in flow from the middle aquifer to the upper aquifer, thus reducing both the quantity and time period over which the water flow to the marsh will be necessary to compensate for the effects of the groundwater drawdown.

Observed heads in the volcanic and middle aquifers during pumping will demonstrate which of the predicted cases best represents reality, and the corresponding likely water replacement volumes required for mitigation of pumping effects.

6.0 CONCLUSIONS

The base case of the groundwater model predicts that, as a result of 40 years of pumping groundwater at the maximum proposed annual pumping rate of 3,000 gpm, the maximum groundwater level drawdown from the project would be 85 ft in the lower (volcanic) aquifer, less than 4 ft in the middle aquifer, and less than 0.5 ft in the upper aquiferThe predicted area of drawdown in the upper aquifer is in the vicinity of the Denton well and Banegas Ranch well No. 2. The base-case model also predicts:

- approximately 1 percent (12 gpm or 19 ac-ft/yr) reduction in the flow of water out of the Big Sandy basin at Granite Gorge
- approximately 0.2 percent (17 gpm or 27 ac-ft/yr) reduction in outflow from evapotranspiration
- approximately 2.5 percent (142 gpm or 229 ac-ft/yr) reduction in outflow at the marsh near the Denton well as a result of 40 years of pumping

These flow reductions add to a predicted maximum drop in flow rates to the river alluvium of approximately 0.5 percent (171 gpm or 275 ac-ft/yr).

For each of the sensitivity analysis groundwater model runs, a different model parameter (such as specific yield or hydraulic conductivity) was altered. Most of the sensitivity analyses produced results that were consistent with the aquifer test results and an acceptable model calibration, but some did not, and these cases were judged to be unrealistic. Of all of those model run cases that were consistent with the aquifer test results and observed heads at the site, and therefore judged to be feasible, one run showed that the maximum predicted groundwater level drawdown in the upper aquifer from the project (after 40 years of pumping groundwater at the same maximum proposed annual pumping rate of 3,000 gpm) was approximately 85 ft in the volcanic (lower) aquifer, 12 ft in the middle aquifer, and less than 1 ft in the upper aquifer. For this worst realistic case, the model also predicted:

- approximately 2 percent (23 gpm or 37 ac-ft/yr) reduction in the flow of water out of the Big Sandy basin at Granite Gorge
- approximately 0.3 percent (33 gpm or 53 ac-ft/yr) reduction in outflow as evapotranspiration
- approximately 5 percent (315 gpm or 508 ac-ft/yr) reduction in outflow at the marsh near the Denton well as a result of 40 years of pumping

These flow reductions add to a predicted maximum drop in flow rates to the river alluvium of approximately 1 percent (371 gpm or 598 ac-ft/yr).

The minimum (best case) predicted groundwater level drawdown from the project was approximately 65 ft in the lower (volcanic) aquifer, less than 0.5 ft in the middle aquifer, and less than 0.1 ft in the upper aquifer, with no reduction in the flow of water out of the Big Sandy basin at Granite Gorge as a result of 40 years of pumping.

The predicted drawdowns in the upper aquifer, and flow reductions, are predicted to be mitigated by water replenishment that matches in volume, timing, and duration the predicted drops in flow rates to the marsh near the Denton well and Granite Gorge.

The volcanic aquifer is predicted to take about 130 years for 90 percent recovery to pre-pumping heads. Observed heads in the volcanic aquifer during actual pumping will demonstrate which of the predicted cases best represents reality, and the corresponding likely water replenishment volumes required for mitigation.

7.0 REFERENCES

ASTM, 1993, D5490-93 Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information, ASTM Annual Book of Standards, v. 4.09, Philadelphia, PA.

ASTM, 1994, D5611-94 Guide for Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application, ASTM Annual Book of Standards, v. 4.09, Philadelphia, PA.

ASTM, 1995, D18.21.95.XX – Draft No. 3. Guide for Calibrating a Ground-Water Flow Model Application, ASTM Technical Committee, Section D18.21.10.

ASTM, 1995[a], D5447-93 Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem, ASTM Annual Book of Standards, v. 4.09, Philadelphia, PA.

ASTM, 1995[b], D5490-93 Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information, ASTM Annual Book of Standards, v. 4.09, Philadelphia, PA.

ASTM, 1995[c], D5609-94 Guide for Defining Boundary Conditions in Ground-Water Flow Modeling, ASTM Annual Book of Standards, v. 4.09, Philadelphia, PA.

ASTM, 1995[d], D5610-94 Guide for Defining Initial Conditions in Ground-Water Flow Modeling, ASTM Annual Book of Standards, v. 4.09, Philadelphia, PA.

ASTM, 1995[e], D5611-94 Guide for Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application, ASTM Annual Book of Standards, v. 4.09, Philadelphia, PA.

ASTM, 1995[f], D5718-95 Guide for Documenting a Ground-Water Flow Model Application, ASTM Annual Book of Standards, v. 4.09, Philadelphia, PA.

Ball, J.T., J.B. Picone, and P.D. Ross. 1994. Evapotranspiration by riparian vegetation along the lower Colorado River. Desert Research Institute, Reno, Nevada. Cady, C.V., 1981. Map Showing Ground-Water Conditions in the Big Sandy Area, Yavapai and Mohave Counties, Arizona – 1980: Arizona Department of Water Resources Hydrologic Map Series Report Number 5: prepared in cooperation with the U.S. Geological Survey, June 1981.

Davidson, E.S., 1973. Water-Resources Appraisal of the Big Sandy Area, Mohave County, Arizona: Arizona Water Commission Bulletin 6, prepared by the Geological Survey, United States Department of the Interior, December 1973.

Domenico, P.A. ,1972. Concepts and Models in Groundwater Hydrology. New York: McGraw-Hill.

Environmental Protection Agency, 1992 Quality Assurance and Quality Control in the Development and Application of Ground-Water Models, EPA/600/R-93/011

FAO website 2001, FAO Irrigation and Drainage Paper 56.

Hanson, R.L., 1991, Evapotranspiration and Droughts, in Paulson, R.W., Chase, E.B., Roberts, R.S., and Moody, D.W., Compilers, National Water Summary 1988-89--Hydrologic Events and Floods and Droughts: U.S. Geological Survey Water-Supply Paper 2375, p. 99-104.

Lease, L.W., 1981. Summary Geologic Report or Drilling in Western Prescott and Williams. Quadrangles, Mohave County, AZ. U.S. Department of Energy Report GJBX-293(81).

Lines, Gregory C., 1999. Riparian Vegetation Along the Mojave River; in Proceedings of Mojave Desert Science Symposium.

Manera, 2000. Water Resources of the Southern Portion of the Big Sandy Valley, Wickieup, Mohave County, Arizona.

Morris, D.A., and A.I. Johnson, 1967. Summary of Hydrologic and Physical Properties of Rock and Soil Materials, as Analyzed by the Hydrologic Laboratory of the U.S. Geological Survey 1948-60. USGS Water Supply Paper 1839-D.

National Research Council, 1990. Groundwater Models, Scientific and Regulatory Applications. National Academy Press, Washington, D.C.

Remick, W.H., 1981. Map Showing Ground-Water Conditions in the Hualapai Basin Area, Mohave, Coconino, and Yavapai Counties, Arizona – 1980: Arizona Department of Water Resources Hydrologic Map Series Report Number 4: prepared in cooperation with the U.S. Geological Survey, May 1981.

Schafer, D., 2000. Aquifer Test Analysis, Big Sandy Energy Project, Wickieup, Mohave County, Arizona.

Singhal, B.B.S., and R.P. Gupta, 1999. Applied Hydrogeology of Fractured Rocks. Dordrecht: Kluwer Academic Publishers.

Trauger, F.D., 1972. Water Resources and Geology of Grant County, New Mexico, Hydrogeologic Report 2, New Mexico State Bureau of Mines and Mineral Resources.

USGS, 2000. U.S. Geological Survey Internet Site: data downloaded August 2000.

Wilson, L.G., DeCook, K.J., and Neuman, S.P., 1980. Final Report, Regional Recharge Research for Southwest Alluvial Basins: sponsored by the U.S. Geological Survey, Contract No. 14-08-0001-18257, The University of Arizona, June 30, 1980.

FIGURES

APPENDIX A

GROUNDWATER MODEL DESCRIPTION

MODFLOW96

NAME

MODFLOW96 - Modular three-dimensional finite-difference ground-water flow model

ABSTRACT

MODFLOW is a three-dimensional finite-difference groundwater flow model. It has a modular structure that allows it to be easily modified to adapt the code for a particular application. Many new capabilities have been added to the original model. OFR 96-485 (complete reference below) documents a general update to MODFLOW, which is called MODFLOW-96 in order to distinguish it from earlier versions.

MODFLOW simulates steady and nonsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal direction aligned with the grid axes and the anisotropy ratio between horizontal coordinate directions fixed in any one layer), and the storage coefficient may be heterogeneous. The model requires input of the ratio of vertical hydraulic conductivity to distance between vertically adjacent block centers. Specified head and specified flux boundaries can be simulated as can a head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modeled area at a rate proportional to the current head difference between a "source" of water outside the modeled area and the boundary block. MODFLOW is currently the most used numerical model in the U.S. Geological Survey for groundwater flow problems. An efficient contouring program is available (Harbaugh 1990) to visualize heads and drawdowns output by the model.

METHOD

The groundwater flow equation is solved using the finite-difference approximation. The flow region is considered to be subdivided into blocks in which the medium properties are assumed to be uniform. The plan view rectangular discretization results from a grid of mutually perpendicular lines that may be variably spaced. The vertical direction zones of varying thickness are transformed into a set of parallel "layers." Several solvers are provided for solving the associated matrix problem; the user can choose the best solver for the particular problem. Mass balances are computed for each time step and as a cumulative volume from each source and type of discharge.

Reference: Above description extracted from USGS Water Resources Application Software.

APPENDICES B AND C

SAMPLE MODEL INPUT AND OUTPUT FILES
(See CD in Pocket)