Review and Recommendations:

WESTCAPS/U.S. Bureau of Reclamation Replication of the Arizona Department of Water Resources Current Trends Alternative Simulation

Prepared for:
U.S. Bureau of Reclamation
Phoenix Office

Prepared by:
Peter A. Mock & Associates, Inc.

December 1, 1998

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CERTIFICATE NO.
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HAND DELIVERY

Warren Greenwell
U.S Bureau of Reclamation
2222 W. Dunlap Avenue
Phoenix, Arizona 85021

Subject: Transmittal of Review Report – BOR Replication of Current Trends Alternative for WESTCAPS

Dear Warren:

Attached are two original, unbound copies of my review of the BOR replication of the Current Trends Alternative for WESTCAPS. Per our conversation with you and Harold Thomas after the ADWR meeting on November 25, 1998, I understand that BOR will make, bind, and distribute copies of this review.

This report completes my work under the IQC purchase order with CH2M HILL, Inc. It was a pleasure working with you, your staff and the WESTCAPS participants. Please call if you have any questions or require additional assistance.

Sincerely,

Peter Mock

Peter Mock, Ph.D., R.G.
President
Peter A. Mock & Associates, Inc.

Copies: Bob Charley/CH2M HILL, Inc./PHX
Craig Yamada/CH2M HILL, Inc./SAC

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Introduction

Peter A. Mock & Associates, Inc. was retained by the U.S. Bureau of Reclamation (BOR) under Purchase Order No. 15688 of CH2M HILL, Inc.' s Federal Prime Indefinite Quantities Contract (IQC) No. 1425-8-PD-30-1023A-028 to provide hydrogeologic expertise and review of the work being conducted by the BOR Phoenix Office for WESTCAPS. WESTCAPS is a coalition of west Salt River Valley (WSRV) Central Arizona Project (CAP) subcontractors who are together evaluating ways to efficiently use their CAP allocations. BOR provides WESTCAPS with technical assistance under a cost-sharing arrangement. The WESTCAPS Groundwater Model project discussed in this report entails the preparation of alternatives for future water demand and supply, and the simulation of the impacts of each alternative on groundwater flow in the WSRV.

The Arizona Department of Water Resources (ADWR) used the U.S. Geological Survey (USGS) MODFLOW groundwater flow simulation software package to prepare a model of the Salt River Valley (the SRV model) and to simulate one scenario of future water demand and supply called the Current Trends Alternative (CTA). The SRV model and the CTA include the WSRV of interest to WESTCAPS. WESTCAPS and BOR originally asked ADWR to operate the SRV model with several new future water demand and supply alternatives developed by WESTCAPS. Due to staff availability and demand for staff at ADWR, ADWR was unable to provide the requested services. WESTCAPS then asked BOR to provide the model operation services with ADWR input. ADWR subsequently provided the groundwater flow model input and output files along with numerous hours of staff time in explaining how ADWR developed the CTA projections with the SRV model.

Purpose

The purpose of this report is to provide the BOR with review and recommendations regarding their operation of the SRV model with files created with a modified GIS interface. Specific input to BOR's work described here includes:

1. following the technical process developed by BOR through meeting participation,
2. advising BOR as to the efficacy of specific actions and recommending improvements as appropriate for project goals, budget and schedule, and
3. inspecting the results of BOR's generation of MODFLOW input files for acceptable agreement with the MODFLOW input files prepared by ADWR.

Scope

The scope of this work includes review and preparation of recommendations for the use by BOR of the BOSS GMS pre- and post-processor for MODFLOW and the ARCView program for GIS file operations on the WESTCAPS Groundwater Model project. Only the MODFLOW recharge and well (pumping) packages of the SRV Model are modified in the WESTCAPS Groundwater Model project; comments on the other MODFLOW packages of the SRV model are not requested at this time.

Verification of the Baseline MODFLOW Model

Verification of the Baseline MODFLOW model (terminology used originally by BOR) consisted of comparing the output from the ADWR-CTA[1] simulations with simulations prepared by BOR from ADWR's input files using BOSS GMS pre- and post-processing software. The output for comparison consisted of the MODFLOW standard output file and plots of water-level elevations simulated for the year 2025.

This verification is a useful first step to show that differences that are later identified between MODFLOW simulations developed with the ADWR GIS interface and those developed with the BOR GIS interface are due solely to differences in the GIS interfaces and not in how BOR handles MODFLOW input and output files. If BOSS GMS had been unable to reproduce the unmodified ADWR MODFLOW results, any inconsistencies would have required resolution prior to comparing the results of ADWR and BOR GIS interfaces. This verification of the Baseline MODFLOW model does not test the application of GIS interfaces in any way.

ADWR's Current Trends Alternative (ADWR-CTA) Model

The input files prepared by ADWR for the ADWR-CTA and the MODFLOW standard output file resulting from ADWR's simulation with their version of MODFLOW were provided to BOR. The MODFLOW standard output file was inspected primarily in terms of ending (year 2025) mass balance components. Simulated ending water-level elevation maps for each model layer are provided in the CTA report.

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[1] Hipke, W., Putman, F., Holway, J.M., and Ferrell, M., 1996. An Application of the Regional Groundwater Flow Model of the Salt River Valley, Arizona Analysis of Future Water Use and Supply Conditions: Current Trends Alternative 1989-2025, Arizona Department of Water Resources Hydrology Division Modeling Report No.11, dated October, 1996, Phoenix, Arizona, 83 p. plus figures.

BOSS GMS Simulation of the ADWR-CTA

BOR started with the ADWR-CTA input files and imported them into BOSS GMS. Then they ran a simulation from BOSS GMS. BOSS GMS also creates a new set of MODFLOW input files which can be run with other versions of MODFLOW.

The ADWR input files required modification before BOSS GMS would correctly read them. Specifically, formats for reading the input data for several two-dimensional arrays required simplification (e.g., removal of line-feed commands and partial line read formats). This modification does not change the input data; instead it makes the input data readable by the current USGS version of MODFLOW and several popular pre- and post- processing packages (e.g., VisualMODFLOW and GroundwaterVistas).

Comparison

BOR presented the comparison of the ADWR and BOR MODFLOW simulations for the ADWR-CTA at a WESTCAPS Technical Committee Meeting on January 23, 1998. The comparison was based on the ending cumulative and instantaneous mass balance components and ending simulated water-level elevations in the three model layers. Mass balance components were the same to all reported significant digits (5) and simulated water-level elevation contours had visibly similar locations and shapes.

Conclusions

The BOSS GMS pre- and post-processor employed by BOR appears to be providing acceptable operation of the ADWR-CTA MODFLOW model input files.

Recommendations

No changes to BOR use of the BOSS GMS MODFLOW pre- and post- processor for this project are recommended at this time. ADWR should be alerted to the format changes required to make ADWR's MODFLOW input files easily readable by several popular pre- and post- processing packages.

Geographic Information Systems (GIS) Interface

A separate issue from MODFLOW operation and results processing is what will be termed here the GIS interface. In essence, the GIS interface converts population projections (in GIS coverage file format) into pumping and recharge projections (in MODFLOW input file format). A coverage is an areal plot of shapes with associated data. The GIS interface takes as input a digital population projection coverage from the Maricopa Association of Governments (MAG), the model grid coverage, the water planning area (WPA) coverage, and a variety of information and assumptions on well pumping rates and how to meet water demand with various sources of supply. The GIS interface provides as output groundwater pumping rates and recharge rates by stress period. Only the well and recharge packages of the ADWR-CTA MODFLOW model input files are modified with the BOR GIS interface.

In producing the CTA model runs, ADWR used a combination of ARC/INFO, FoxPro, and BASIC programs to develop their GIS interface. BOR has taken selected calculations used by ADWR that required modification for the various WESTCAPS alternatives and streamlined them into an ARCView program. Intermediate computer files developed by ADWR that did not require modification for WESTCAPS were obtained from ADWR and used directly.

ADWR's GIS Interface

For a description of the elements of ADWR's CTA GIS interface, the reader is referred to their report. Significant detail in implementation was not provided in the report, consistent with the broad audience for which the report was intended. A variety of programs and files were developed and used by ADWR in their GIS interface, including ARC/INFO, FoxPro and BASIC. The chain of applications of the various programs is complex and challenging to follow and reconstruct.

ADWR staff who completed the work on the CTA model attended numerous meetings and provided individual digital files and program scripts to explain the details of the GIS interface implementation. The input of Wes Hipke (ADWR), Jim Swanson (formerly ADWR, currently City of Surprise), and Brad Hill (formerly ADWR, currently City of Peoria) in Groundwater Model Subcommittee meetings was a primary factor in BOR being able to reconstruct numerous details of the logic used in ADWR's GIS interface for the CTA.

BOR's GIS Interface

BOR sought to reproduce the computer instructions developed by ADWR, but gather those instructions that would be modified for WESTCAPS alternatives into a cohesive unit. BOR selected ARCView as a software foundation because it is sufficiently powerful to process GIS coverages while being sufficiently affordable for WESTCAPS members to purchase and use themselves. BOR appears to have implemented the logic for each calculation as described by ADWR in the CTA report and in numerous programs provided and explained separately by ADWR.

Comparison

In developing the BOR GIS interface, BOR had some challenges in reproducing intermediate results of ADWR. BOR compared selected intermediate coverages developed by their GIS interface with those sent by ADWR from their archived digital files. BOR also compared the MODFLOW well and recharge input files developed with the BOR GIS interface with those developed by ADWR for the CTA. Differences in values were found in these comparisons. The primary difference was a lower total pumping rate developed by BOR compared to that developed by ADWR for the CTA.

The differences between BOR and ADWR results were discussed at length with ADWR staff and ADWR typically confirmed that BOR had used the correct computer instructions with the correct files. The magnitude of the difference in total pumping volume was typically 7% with the BOR results being less than the ADWR results. The locations of the differences were also plotted for selected time periods by BOR and reviewed with the Groundwater Model Subcommittee of WESTCAPS. Three primary reasons were identified by BOR for the differences in pumping rates (comments in parentheses):

1. The ADWR CTA applied pumping at rates greater than the total water demand within some WPAs.
2. The ADWR CTA applied different populations than BOR applied in some WPAs.
3. The ADWR CTA resulted in a slower spread of municipal water use, called the urbanization rate, than that resulting from BOR's implementation of ADWR's computer instructions. Slower urbanization leaves high-capacity agricultural wells operating for longer periods of time.

Conclusions

The ADWR GIS interface, as described in the CTA report and elaborated upon at length in meetings, appears to be a major advancement in data processing for groundwater simulation development at the basin scale. Specifically, water demand and supply data and assumptions for a major southwestern U.S. metropolitan area have been successfully translated into computer instructions. In contrast to many GIS applications that merely present graphical information, ADWR's GIS interface is an exemplary use of GIS technology in that it makes numerous, involved calculations with the data tied to spatial representations. However, the ADWR GIS interface results for the CTA can not currently be exactly reproduced because time (7 years) has lead to loss of some details – human memory and computer files – needed to recreate ADWR's original work on the GIS interface. The ADWR GIS interface is difficult to use and document because it is a diverse collection of data files and programs for operating on these data files.

The result of BOR's work appears to be a cost-effective and streamlined package (compared to ADWR's original collection of programs) for preparing well and recharge package inputs to MODFLOW for the SRV model. A water provider or other entity can start from files provided by BOR, modify them as necessary with ARCView, and produce MODFLOW input files. An entity's technical staff or consultants proficient in GIS and groundwater model operation (and interpretation) should be able to conduct their own simulations of future groundwater flow in the Salt River Valley. The arrival of this product represents a valuable service and a unique new opportunity in the history of basin-scale model development and use in Arizona. In the past, only the USGS or ADWR had the facilities and staff to conduct such projections.

The BOR GIS interface can be considered an improvement upon the ADWR GIS interface for WESTCAPS analysis of future groundwater conditions for the following reasons:

1. BOR had the advantage of viewing ADWR's files and operations in hindsight and designing an improved development and documentation system
2. BOR uses one program (ARCView) as the tool for operating on selected GIS coverages
3. the magnitude of the cumulative pumping volume difference is less than 7%
4. the three sources of differences in pumping rates produced by the GIS interfaces (ADWR and BOR) appear to have been identified by BOR and they appear to be instances where the BOR calculations are corrections of unexplained inconsistencies in the ADWR GIS interface (e.g., WPA pumping rates larger than total water demand, transfer of population projections or housing unit values, implementation of urbanization rate calculations)
5. ADWR has not been able to find all of the computer files used in the calculations resulting in the three identified sources of differences.

The differences between the ADWR and BOR GIS interface results are attributed here to the expected situation of identifying and correcting minor (from an overall perspective) inconsistencies in a large and complex calculation process when a separate entity (in this case, BOR) creates a second-generation software application. The WESTCAPS Groundwater Model project appears to have improved upon the process used to create ADWR's CTA.

Recommendations

To allow closure of the GIS interface development process, the goal of exactly replicating the results of ADWR's GIS interface for the CTA should be abandoned. This recommendation is based on two premises: 1) ADWR is currently unable to find all of the original CTA files, and 2) the BOR GIS interface appears to be an improvement for reasons given above. To allow commencement of alternatives development and simulations for planning comparisons, a new "standard" CTA developed with BOR's GIS interface should replace the CTA developed with ADWR's GIS interface and documented in the CTA report. A formal acceptance of the CTA developed with BOR's GIS interface should be requested from ADWR. To avoid difficulties similar to those encountered here in reproducing previous results, BOR should continue to write all files and program instruction listings used for each alternative to a separate compact disk to document the development of each alternative.

Alternatives Development

For the WESTCAPS Groundwater Model Project, several alternatives will be prepared through the GIS interface and simulated with the ADWR SRV model. Review and comment on the alternatives developed by BOR is most effectively accomplished by inspecting the CTA developed with the BOR GIS interface since it can be compared to ADWR's CTA. The remainder of the alternatives will use the BOR GIS interface with different input assumptions. Therefore, acceptance of the BOR CTA MODFLOW results indicates that BOR's BOSS GMS and GIS interface tools would also be expected to provide essentially the same process as ADWR created for the CTA, when applied to development of the remaining alternatives.

The approach used in this review was to run both the ADWR and BOR CTA input files with a current USGS version of MODFLOW and systematically inspect and compare the results. The current version of MODFLOW selected for this work is the version downloaded from the USGS Internet site[2]. Using a current MODFLOW version simplifies the process of extracting information from the two models for comparison. To run the ADWR-CTA and BOR-CTA input data files with the current MODFLOW model, a new file was needed, called a name file. The name file was easily created with a text editor and simply lists the requested input and output files to be processed by the current MODFLOW model.

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[2] http://www.usgs.gov/software/modflow-96.html; MODFLOW96, Version 3.2, created 1/9/98.

Additional programs were employed to efficiently extract the following information from each MODFLOW simulation (ADWR-CTA and BOR-CTA):

1. Mass balance components by selected zones
2. Cell conversions from wet to dry or dry to wet.
3. Simulated water-level elevations by layer at a selected time
4. Simulated water-level elevations at selected points over time

The analysis of this extracted information improves (compared to review of output listings) the ability to detect differences and assess their magnitudes between the two models.

ADWR-CTA

The ADWR-CTA files ran with the current MODFLOW model after simplification of the two-dimensional array input read formats. The mass balance components calculated by ADWR with their MODFLOW model and here with the current MODFLOW model were similar in value (a few percent of less in difference) despite the fact that the current MODFLOW model has been improved over earlier versions to accumulate mass balances in double precision.

Although the scope of this review includes only the well and recharge packages, some features of the ADWR-CTA model (which are equally true of the BOR-CTA model) were noted that deserve comment. Specifically, some caveats are in order concerning the ability of the SRV model to produce accurate results. These caveats are typical of large and complex groundwater models and do not indicate that the SRV model is not useful for the purposes of the WESTCAPS Groundwater Model project.

An overall improvement in model operation can be achieved by reducing the criterion for solution precision. A smaller closure criterion enforces greater accuracy from the beginning of the simulation and eliminates incorrect transmissivity, layer-type and wet-dry conversions that affect later results in a possibly unpredictable ways. The closure criterion for the SOR iterative solver was set in the input files provided by ADWR to 0.5 feet. This value is relatively high and results in mass balance errors approaching 1%, which are generally acceptable but could be improved. A preliminary run indicated that setting the closure criterion down to 0.05 feet (with a required change in the over-relaxation parameter from 1.00 to 1.05) was successful (ran to completion and reduced the mass balance errors to a few tenths of a percent) and resulted in changes of a few percent in the mass balance components, likely because of improved accuracy. This preliminary run was only undertaken to test the possibility of improving accuracy. For consistency in comparison, the original closure criterion (0.5 feet) was restored and used for all comparisons discussed here.

The SRV model applies several features of MODFLOW that are powerful for realistic simulation, but require some consideration when simulating new alternatives with pumping and recharge at different rates and locations. The five features of note include:

1. the water-table option that updates the transmissivity of a layer with each estimate of the solver package on its way to a solution for water-level elevation at each time step
2. the option for layer conversions from water table to confined and vice versa
3. the option that allows a model cell to become saturated or unsaturated based on the water-level elevations in the cell and in surrounding cells ("wet-dry" conversion)
4. the feature that wells are eliminated during a stress period when a cell becomes unsaturated
5. the option to allow recharge to be applied to the highest active layer at each locations

Each of these features results in sudden changes in the stresses being applied to individual cells during the simulations. Sudden changes in stresses lead to sudden changes in water-level elevations which require some consideration in terms of the mathematical solutions applied in MODFLOW. These five features can interact to produce oscillations in the estimated water-level elevations during each time step and the result is lesser accuracy and longer simulation times. In some cases the oscillations can become excessive and cause MODFLOW to stop before completion of the requested simulation.

Potential actions for reducing the impact of the water-table and layer-conversion options include the specification of time step duration and the use of solver options that produce the smallest oscillations in estimated water-level elevation during each iteration. Smaller oscillations produce smaller swings in transmissivity and smoother transitions from one layer type to another. Shorter time step durations (to a point) typically produce smaller oscillations. The SOR solver can typically be set to produce the least oscillation.

Potential actions for reducing the impact of the wet-dry conversions include those noted for the water-table option. Additional actions specific to the wet-dry option include selection of the equation for monitoring wet-dry conversions and adjustment of the thresholds for wet-dry conversions.

The timing of changes in recharge location or of wells being eliminated are difficult to anticipate and may be best addressed by noting stress periods where convergence is low or halted and reducing the time step duration in that stress period.

The selection of time step duration may have the potential for making the greatest impact on accurate results with the SRV model. ADWR selected constant time step durations during each stress period, however the largest water-level elevation changes are expected at the beginning of each stress period when stresses (pumping, recharge, etc.) change in a step-wise way. Oscillations typically occur when simulation of larger head changes are attempted and smaller head changes occur when shorter periods of time are considered. Therefore, smaller time steps are desirable, especially at the beginning of each stress period.

In summary, the ADWR-CTA model runs to completion with acceptable results. However, suggestions have been provided for mitigation of problems that could arise in the operation of the MODFLOW files developed by ADWR for well or recharge package inputs that differ from those of the CTA.

BOR-CTA

The BOR-CTA files (i.e., ADWR CTA files for all but the well and recharge packages that were produced by the BOR GIS interface) ran without modification on the current MODFLOW model. The model ran to completion (simulated 2025) and mass balance components were close in value to those provided in BOR's output files from BOSS GMS. The caveats and suggestions described above for the SRV model are as applicable to the BOR-CTA model as they are to the ADWR-CTA model.

Comparison

Several comparisons were made between the ADWR and BOR CTA model runs:

1. overall model mass balance components at selected times,
2. distribution of mass balance components in different parts of the Salt River Valley,
3. wet-dry conversions,
4. calculated water-level elevation surfaces across the Salt River Valley in the three model layers at the end of the simulations, and
5. hydrographs (water-level elevation time series) for selected locations in the Salt River Valley.

A detailed comparison is provided in Appendix A. Together, these comparisons represent a comprehensive inspection of both models and allow for identification and quantification of primary differences between the models.

Conclusions

Overall, the ADWR-CTA and BOR-CTA models are very similar in simulated mass balance components, wet-dry conversions, and water-level elevations. Differences are those expected in response to reduced pumping rates in the BOR-CTA as compared to the ADWR-CTA. As noted under the evaluation of the GIS interface, the lower pumping rates in the BOR model are the result of GIS calculations that appear to be more clearly supported by available documentation. The results of the lesser pumping rates in the BOR CTA model are to increase the amount of water entering storage in areas of rising water levels and decrease the amount of water being withdrawn from storage in areas of declining water levels. These results are apparent from inspection of the mass balance components and supported by inspection of wet-dry conversions.

Recommendations

The BOR-CTA model should replace the ADWR-CTA model as a baseline for planning comparisons. The two models provide similar results, but the BOR-CTA model is to be preferred due to recent improvements and streamlined GIS interface.

Appendix A

Detailed Comparison of the ADWR CTA and BOR CTA MODFLOW Simulations

This appendix provides a detailed comparison of the ADWR-CTA and BOR-CTA MODFLOW simulations. The differences between the two models in terms of input occur only in the well and recharge files. The well and recharge input files for the two models were created with separate GIS interfaces as discussed in this report.

The detailed comparison starts with the total cumulative mass balances and then considers the details of instantaneous mass balances at specific times and in specific areas. Then, the wet-dry conversions are compared between the two models. Next, the comparison reviews the contours of water-level elevations in each layer at the end of the simulated period (2025). Finally, simulated water-level elevation results are compared at selected locations over the entire simulation time of 37 years.

Overall Model Mass Balance Components

Comparison of the simulated total amounts of water moving through the SRV model during 37 years of simulated groundwater flow provides the broadest perspective for the ADWR-CTA and BOR-CTA models. Table A-1 presents the cumulative mass balance components for the two models as calculated by the current USGS MODFLOW model. The top half of Table A-1 has the units used in MODFLOW (cubic feet), while the lower half of Table A-1 translates the values into common water-planning units: acre-feet.

In both models, recharge and storage (41.3 or 43.6 million acre-feet) are the largest components in the inflow category while pumping and storage (42.9 or 45.2 million acre-feet) are the largest components in the outflow category. In general, the BOR-CTA model moved about 5% less water through the simulated SRV groundwater system than the ADWR-CTA model. The 7% less pumping (2.62 million acre-feet) applied to the BOR-CTA model appears to be primarily balanced by a 23% decrease in

TABLE A-1
TOTAL CUMULATIVE WATER VOLUMES (37 years)
Current Trends Alternative MODFLOW Model

	ADWR CTA (cubic feet)	BOR CTA (cubic feet)	Differences (BOR-ADWR) (cubic feet)	Relative Differences (BOR-ADWR)/ADWR (%)
IN				
Recharge	1,452,400,000,000	1,452,500,000,000	100,000,000	0.01%
Storage	448,208,470,000	346,976,551,000	-101,231,919,000	-22.59%
River	81,381,736,400	86,318,817,300	4,937,080,900	6.07%
Wells	53,779,173,400	49,909,612,500	-3,869,560,900	-7.20%
Constant Head	15,534,189,600	15,602,584,600	68,395,000	0.44%
Total IN	**2,051,303,569,400**	**1,951,307,565,400**	-99,996,004,000	**-4.87%**
OUT				
Wells	1,725,700,000,000	1,611,400,000,000	-114,300,000,000	-6.62%
Storage	243,616,743,000	258,916,549,000	15,299,806,000	6.28%
ET	66,582,446,100	66,270,380,000	-312,066,100	-0.47%
River	16,572,335,100	15,528,336,400	-1,043,998,700	-6.30%
Constant Head	7,643,837,440	7,533,656,060	-110,181,380	-1.44%
Total OUT	**2,060,115,361,640**	**1,959,648,921,460**	-100,466,440,180	**-4.88%**
IN-OUT (cubic feet)	**-8,811,792,240**	**-8,341,356,060**	**470,436,180**	
IN-OUT (RPD)	**-0.43%**	**-0.43%**	**-0.47%**	

	ADWR CTA (acre-feet)	BOR CTA (acre-feet)	Differences (BOR-ADWR) (acre-feet)	Relative Differences (BOR-ADWR)/ADWR (%)
IN				
Recharge	33,342,516	33,344,812	2,296	0.01%
Storage	10,289,451	7,965,486	-2,323,965	-22.59%
River	1,868,268	1,981,607	113,340	6.07%
Wells	1,234,600	1,145,767	-88,833	-7.20%
Constant Head	356,616	358,186	1,570	0.44%
Total IN	**47,091,450**	**44,795,858**	-2,295,592	**-4.87%**
OUT				
Wells	39,616,621	36,992,654	-2,623,967	-6.62%
Storage	5,592,671	5,943,906	351,235	6.28%
ET	1,528,523	1,521,359	-7,164	-0.47%
River	380,448	356,482	-23,967	-6.30%
Constant Head	175,478	172,949	-2,529	-1.44%
Total OUT	**47,293,741**	**44,987,349**	-2,306,392	**-4.88%**
IN-OUT (Acre-feet)	**-202,291**	**-191,491**	**10,800**	
IN-OUT (RPD)	**-0.43%**	**-0.43%**	**-0.47%**	

water removed from storage (2.32 million acre-feet) and a 6% increase in water added to storage (0.35 million acre-feet). The percentages discussed here are the differences from each ADWR-CTA mass balance component. The percentages are not comparable, but the total volumes given in parentheses are comparable. Of lesser importance from a total cumulative volume perspective are changes of 6% in river in/outflow and changes of less than 2% in evapotranspiration and constant head fluxes.

Turning to the differences in mass balance components over time, Table A-2 presents the instantaneous fluxes in acre-feet per year (af/yr) calculated by the two models for 1991, 1995, 2010, and 2025. These are points in time selected by ADWR for description in the CTA report. The cumulative volumes in acre-feet from Table A-1 are also presented in Table 2 for comparison.

Differences between the ADWR-CTA and BOR-CTA mass balance components are shown at the bottom of Table A-2. Differences greater than approximately 10% in any category are given a gray background. As in Table A-1, the differences are presented as a percent of each ADWR mass balance component. In most cases, the differences increase with time. The differences between BOR and ADWR pumping rates increase from less than 1% in 1991 to more than 11% in 2025. The increasing nature of the differences between ADWR and BOR pumping rates over time is a reasonable explanation for the increasing differences in storage (in or out) and constant head fluxes with time. River leakage and evapotranspiration differences increase and then decrease with time, indicating a more complex interaction of pumping differences and these mass balance components in the SRV model.

Visual comparison of the mass balance components calculated by the two models is provided for in Figures A-1 and A-2. That the shapes of the graphs are quite similar indicates, as do the values in Tables A-1 and A-2, that the two models are simulating system responses in the Salt River Valley in similar ways.

TABLE A-2
MASS BALANCES OVER TIME CALCULATED FOR THE ADWR AND BOR Current Trends Alternative MODFLOW MODELS

	ADWR-CTA (af/yr)					
IN	1991 (af/yr)	1995 (af/yr)	2010 (af/yr)	2025 (af/yr)	37 yr cumulative (af)	37 yr cumulative (% of in or out)
Recharge	908,394	957,245	898,339	773,999	33,342,516	70.80%
Storage	158,586	115,022	211,073	445,969	10,289,486	21.85%
River Leakage	41,292	34,099	50,482	88,678	1,868,274	3.97%
Wells	33,928	33,928	33,245	32,752	1,234,596	2.62%
Constant Head	14,670	13,052	8,070	7,171	356,612	0.76%
TOTAL IN	1,156,870	1,153,347	1,201,209	1,348,569	47,091,483	100.00%
OUT	(af/yr)	(af/yr)	(af/yr)	(af/yr)	(af)	(% of in/out)
Wells	958,083	896,496	1,045,562	1,279,427	39,616,621	83.77%
Storage	147,542	204,185	100,953	25,215	5,592,746	11.83%
ET	41,916	43,700	41,358	35,914	1,528,512	3.23%
River Leakage	2,842	6,633	13,228	10,959	380,441	0.80%
Constant Head	1,149	1,219	5,602	8,047	175,478	0.37%
TOTAL OUT	1,151,533	1,152,233	1,206,704	1,359,562	47,293,797	100.00%

	BOR-CTA (af/yr)					
IN	1991 (af/yr)	1995 (af/yr)	2010 (af/yr)	2025 (af/yr)	37 yr cumulative (af)	37 yr cumulative (% of in/out)
Recharge	908,394	957,245	898,339	774,125	33,344,812	74.44%
Storage	155,812	103,526	142,590	300,807	7,965,565	17.78%
River Leakage	41,402	34,296	55,339	92,440	1,981,612	4.42%
Wells	31,655	31,478	31,216	29,901	1,145,776	2.56%
Constant Head	14,670	13,098	8,112	7,243	358,196	0.80%
TOTAL IN	1,151,933	1,139,643	1,135,596	1,204,516	44,795,960	100.00%
OUT	(af/yr)	(af/yr)	(af/yr)	(af/yr)	(af)	(% of in/out)
Wells	952,050	867,084	967,803	1,129,690	36,992,654	82.23%
Storage	148,782	216,972	114,377	35,186	5,943,985	13.21%
ET	41,895	43,716	41,057	35,594	1,521,350	3.38%
River Leakage	2,838	6,620	11,960	10,019	356,474	0.79%
Constant Head	1,149	1,213	5,565	7,864	172,950	0.38%
TOTAL OUT	1,146,713	1,135,605	1,140,761	1,218,354	44,987,413	100.00%

	Differences: (BOR-ADWR)/ADWR				
IN	1991 (%)	1995 (%)	2010 (%)	2025 (%)	37 yr cumulative (%)
Recharge	0.00%	0.00%	0.00%	0.02%	0.01%
Storage	-1.75%	-9.99%	-32.45%	-32.55%	-22.59%
River Leakage	0.27%	0.58%	9.62%	4.24%	6.07%
Wells	-6.70%	-7.22%	-6.10%	-8.70%	-7.19%
Constant Head	0.00%	0.35%	0.52%	1.00%	0.44%
OUT	(%)	(%)	(%)	(%)	(%)
Wells	-0.63%	-3.28%	-7.44%	-11.70%	-6.62%
Storage	0.84%	6.26%	13.30%	39.55%	6.28%
ET	-0.05%	0.04%	-0.73%	-0.89%	-0.47%
River Leakage	-0.17%	-0.20%	-9.59%	-8.58%	-6.30%
Constant Head	-0.01%	-0.50%	-0.66%	-2.27%	-1.44%

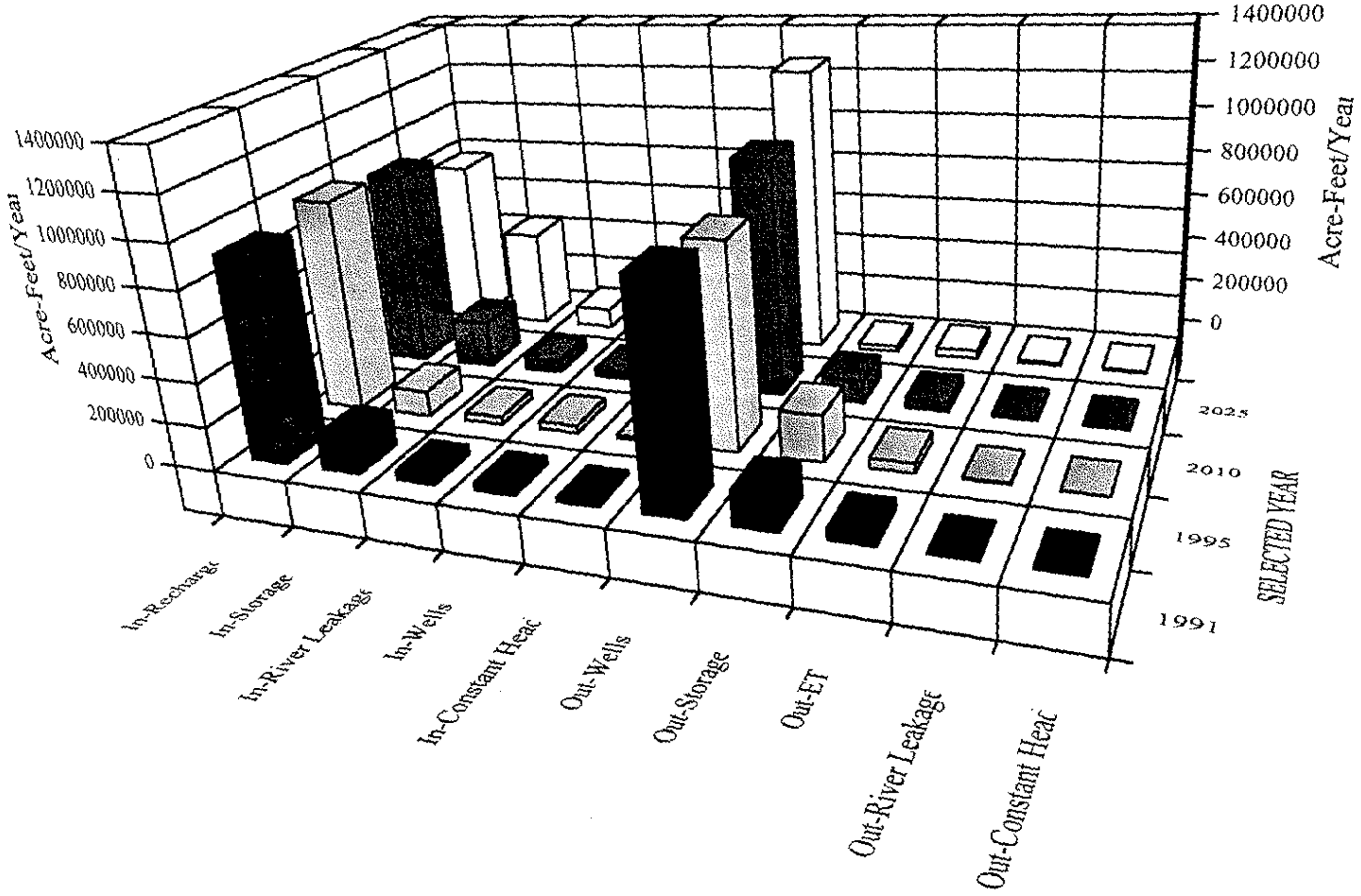

Figure A-1:
Water Balance Analysis of MODFLOW Model:
ADWR - Current Trends - as Run by ADWR

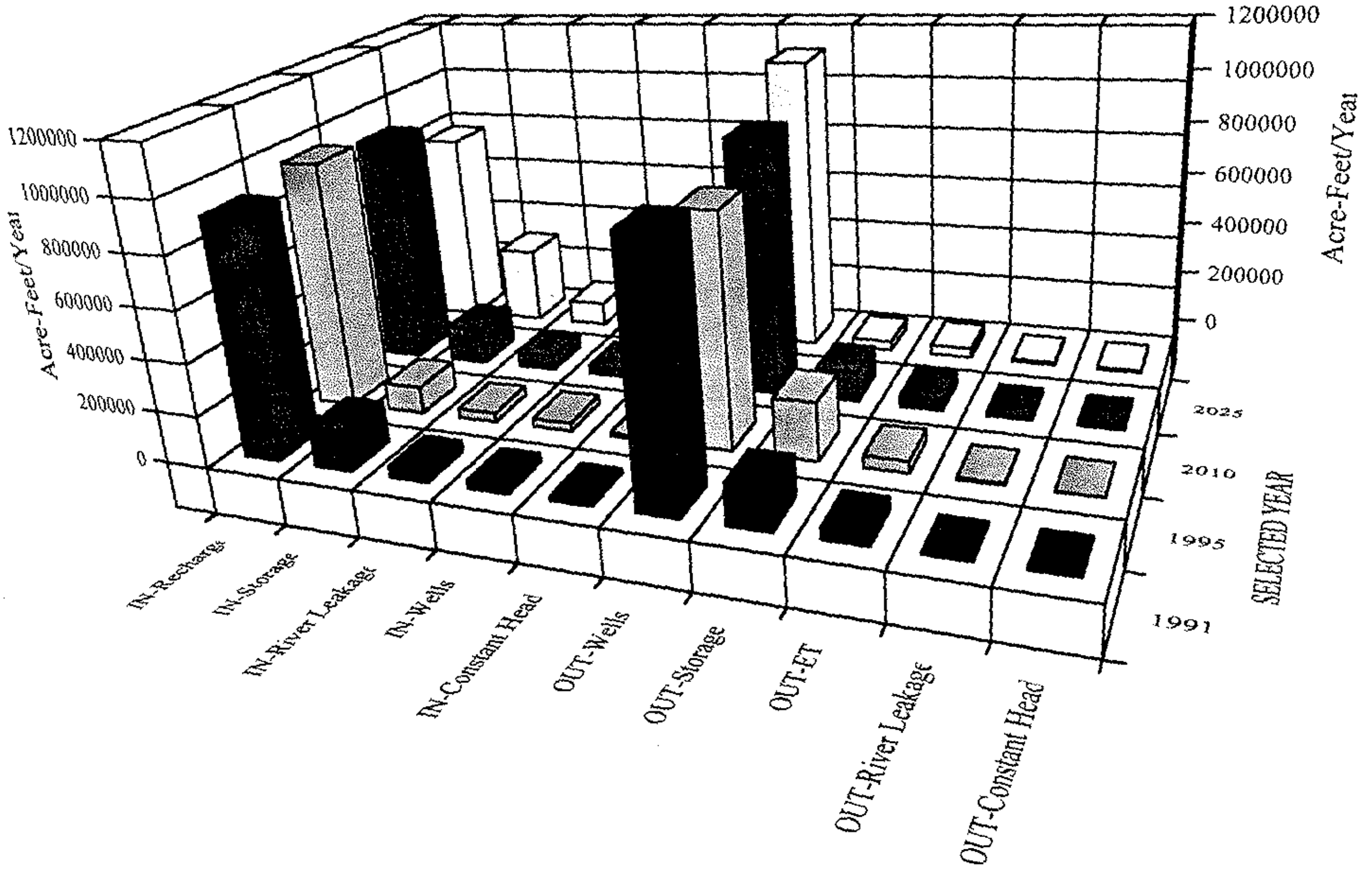

Figure A-2:
Water Balance Analysis of MODFLOW Model:
BOR - Current Trends - as Run by BOR

Mass Balance Components in Selected Zones

The movement of water in the SRV model can next be viewed from the perspective of model sub-basins and model layers. The interest here is in monitoring large-scale flows within the SRV model and note whether there are any substantial differences in the west Salt River Valley. In the SRV model, there are three sub-basins:

1. West Salt River Valley [WSRV],
2. East Salt River Valley [ESRV], and
3. part of the Lower Santa Cruz Basin primarily in the Gila River Indian Community [LSC/GRIC].

The SRV Model has three layers:

1. Upper Alluvial Unit [UAU],
2. Middle Alluvial Unit [MAU] and
3. Lower Alluvial Unit plus Red Unit [LAU].

The reader is referred to the CTA report for the delineation of sub-basins and layers. Figure A-3 is modified from the CTA Report for easy reference and for later reference to hydrograph locations. The mass balance components compiled in Table A-3 address flow within and between these divisions.

The upper half of Table A-3 presents the mass balance components at the end of the simulations (2025) for the three sub-basins. Overall, the ADWR-CTA and BOR-CTA mass-balance components separated by sub-basin are similar in direction (sign) and magnitude. More components are within 10% of each other than otherwise. With the exception of pumping and storage, the total rates represented by the differences greater than 10% are relatively small. This indicates that the flow between and within sub-basins is similar in the two models. There are greater differences between the two models in the ESRV, primarily associated with the far northern end of Phoenix and near the GRUSP recharge project where most of the rising water-level and resulting re-wetting activity is occurring.

Figure A-3: Location Map - Sub-basin Boundaries and Locations for Hydrographs

(Modified from Figure 1 of ADWR's CTA Report)

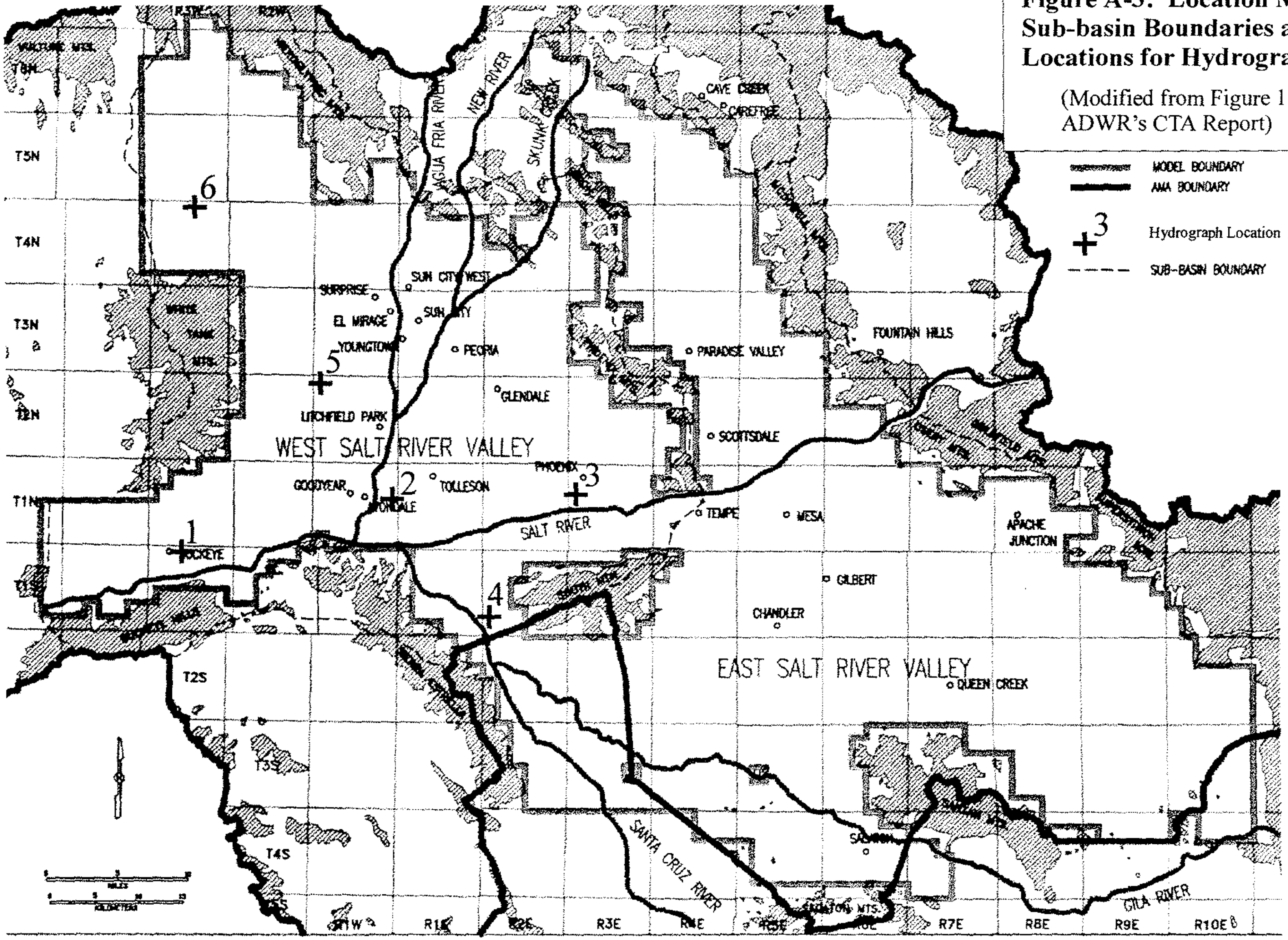

TABLE A-3
ADWR AND BOR Current Trends Alternative MODFLOW MODELS

(MASS BALANCE COMPONENTS in 2025 BY SUB-BASIN)

acre-feet/year	WSRV			ESRV			LSC/GRIC		
IN	ADWR	BOR	DIFF	ADWR	BOR	DIFF	ADWR	BOR	DIFF
Recharge	314,792	315,169	0.12%	306,086	303,103	-0.97%	19,875	19,875	0.00%
Storage	255,425	184,930	**-27.60%**	176,727	103,249	**-41.58%**	9,734	7,614	**-21.78%**
River Leakage	88,678	92,440	4.24%	0	0	0.00%	0	0	0.00%
Wells	7,168	7,596	5.97%	20,286	22,290	**9.88%**	0	0	0.00%
Constant Head	7,171	7,243	1.00%	0	0	0.00%	0	0	0.00%
ESRV	1,227	2,031	**65.53%**	0	0	0.00%	11,867	12,571	5.94%
WSRV	0	0	0.00%	0	0	0.00%	0	0	0.00%
LSC/GRIC	11,102	11,456	3.19%	51	12	**-75.72%**	0	0	0.00%
Re-Wetted	6,539	5,422	**-17.09%**	165,876	165,364	-0.31%	0	0	0.00%
TOTAL IN	692,101	626,286	-9.51%	669,025	594,018	**-11.21%**	41,476	40,061	-3.41%
OUT									
Wells	639,915	578,051	**-9.67%**	603,180	515,089	**-14.60%**	31,074	29,479	-5.13%
Storage	1,426	2,314	**62.28%**	17,422	24,590	**41.14%**	0	0	0.00%
ET	35,914	35,594	-0.89%	0	0	0.00%	0	0	0.00%
River Leakage	10,960	10,018	-8.59%	0	0	0.00%	0	0	0.00%
Constant Head	8,047	7,864	-2.27%	0	0	0.00%	0	0	0.00%
ESRV	0	0	0.00%	0	0	0.00%	51	12	**-75.72%**
WSRV	0	0	0.00%	1,227	2,031	**65.53%**	11,102	11,456	3.19%
LSC/GRIC	0	0	0.00%	11,867	12,571	5.94%	0	0	0.00%
Re-Wetted	2,101	1,409	**-32.91%**	39,500	44,006	**11.41%**	0	0	0.00%
TOTAL OUT	698,363	635,251	-9.04%	673,196	598,287	**-11.13%**	42,228	40,947	-3.03%

(MASS BALANCE COMPONENTS in 2025 BY MODEL LAYER)

acre-feet/year	UAU			MAU			LAU		
IN	ADWR	BOR	DIFF	ADWR	BOR	DIFF	ADWR	BOR	DIFF
Recharge	477,575	477,751	0.04%	141,760	140,981	-0.55%	21,407	19,417	-9.30%
Storage	155,594	119,765	**-23.03%**	184,343	128,580	**-30.25%**	101,950	47,453	**-53.46%**
River Leakage	88,678	92,440	4.24%	0	0	0.00%	0	0	0.00%
Wells	4,488	4,488	0.00%	4,450	4,953	**11.30%**	18,516	20,445	**10.41%**
Constant Head	2,317	2,343	1.12%	2,608	2,633	0.96%	2,246	2,266	0.90%
UAU	0	0	0.00%	472,402	446,996	-5.38%	0	0	0.00%
MAU	19,840	20,360	2.62%	0	0	0.00%	268,264	252,602	-5.84%
LAU	0	0	0.00%	86,863	100,120	**15.26%**	0	0	0.00%
Re-Wetted	16,354	17,154	4.89%	148,128	148,430	0.20%	7,933	5,204	**-34.41%**
TOTAL IN	764,846	734,301	-3.99%	1,040,556	972,693	-6.52%	420,317	347,386	-17.35%
OUT									
Wells	202,225	193,527	-4.30%	738,421	684,626	-7.29%	333,528	244,465	**-26.70%**
Storage	4,814	9,750	**102.54%**	9,270	12,131	**30.86%**	4,765	5,022	5.41%
ET	35,914	35,594	-0.89%	0	0	0.00%	0	0	0.00%
River Leakage	10,960	10,018	-8.59%	0	0	0.00%	0	0	0.00%
Constant Head	3,035	2,972	-2.07%	2,959	2,889	-2.36%	2,053	2,004	-2.42%
UAU	0	0	0.00%	19,840	20,360	2.62%	0	0	0.00%
MAU	472,402	446,996	-5.38%	0	0	0.00%	86,863	100,120	**15.26%**
LAU	0	0	0.00%	268,264	252,602	-5.84%	0	0	0.00%
Re-Wetted	35,176	34,931	-0.70%	6,197	6,300	1.65%	227	4,186	**1741.44%**
TOTAL OUT	764,526	733,788	-4.02%	1,044,951	978,907	-6.32%	427,436	355,796	-16.76%

The lower half of Table A-3 presents the mass balance components at the end of the simulations (2025) for the three model layers. Overall, the ADWR-CTA and BOR-CTA mass-balance components divided by layer are similar in direction (sign) and magnitude. More components are within 10% of each other than otherwise. The largest differences in pumping are now seen to be concentrated in the LAU and flow between the MAU and LAU is different between the two models. The difference in flow between the MAU and LAU is attributed to correction by BOR of pumping rates greater than total demand in the far north end of Phoenix and less dewatering of the MAU in that area in BOR-CTA.

Wet-Dry Conversions

The instances of wet or dry conversions of model cells were extracted from the ADWR-CTA and BOR-CTA standard MODFLOW output files. In terms of total conversions, the ADWR-CTA model had 280 while the BOR-CTA model had 259 (a 7.5% decrease). The BOR-CTA model had fewer conversions to dry, 113, as opposed to 150 dry conversions for the ADWR-CTA model. The BOR-CTA model had more conversions to wet, 146, as opposed to 130 wet conversions for the ADWR-CTA model. These findings are consistent with the conclusion drawn from considering mass balance components that the lesser pumping amounts used in the BOR-CTA model lead to less dewatering in areas of declining water-level elevations and to more build-up in areas of rising water-level elevations. The number of differences in cell conversions, viewed as percentages of ADWR values ranged from 11% to 12%.

Simulated Ending Water-level Elevations

The output of the two models was also compared in terms of the simulated water-level elevations at the end of the simulation period. The water-level elevations for each layer, simulated by each of the two models, were subtracted to create a difference map for each layer. Figures A-4 through A-6 present the differences in simulated water-level elevations between the ADWR-CTA and BOR-CTA models in each of the three model layers.

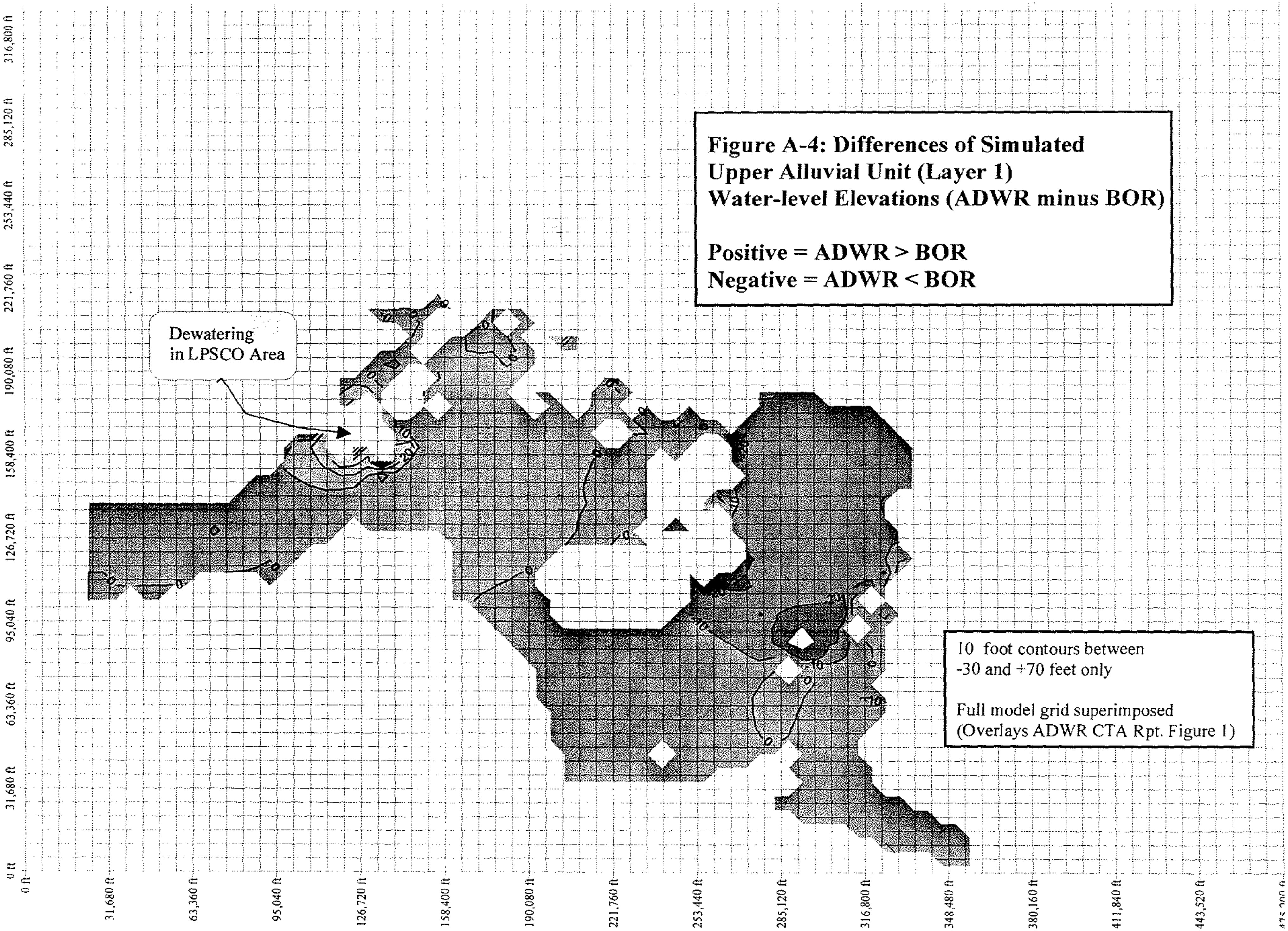
Figure A-4: Differences of Simulated Upper Alluvial Unit (Layer 1) Water-level Elevations (ADWR minus BOR)

Positive = ADWR > BOR
Negative = ADWR < BOR

10 foot contours between
-30 and +70 feet only

Full model grid superimposed
(Overlays ADWR CTA Rpt. Figure 1)

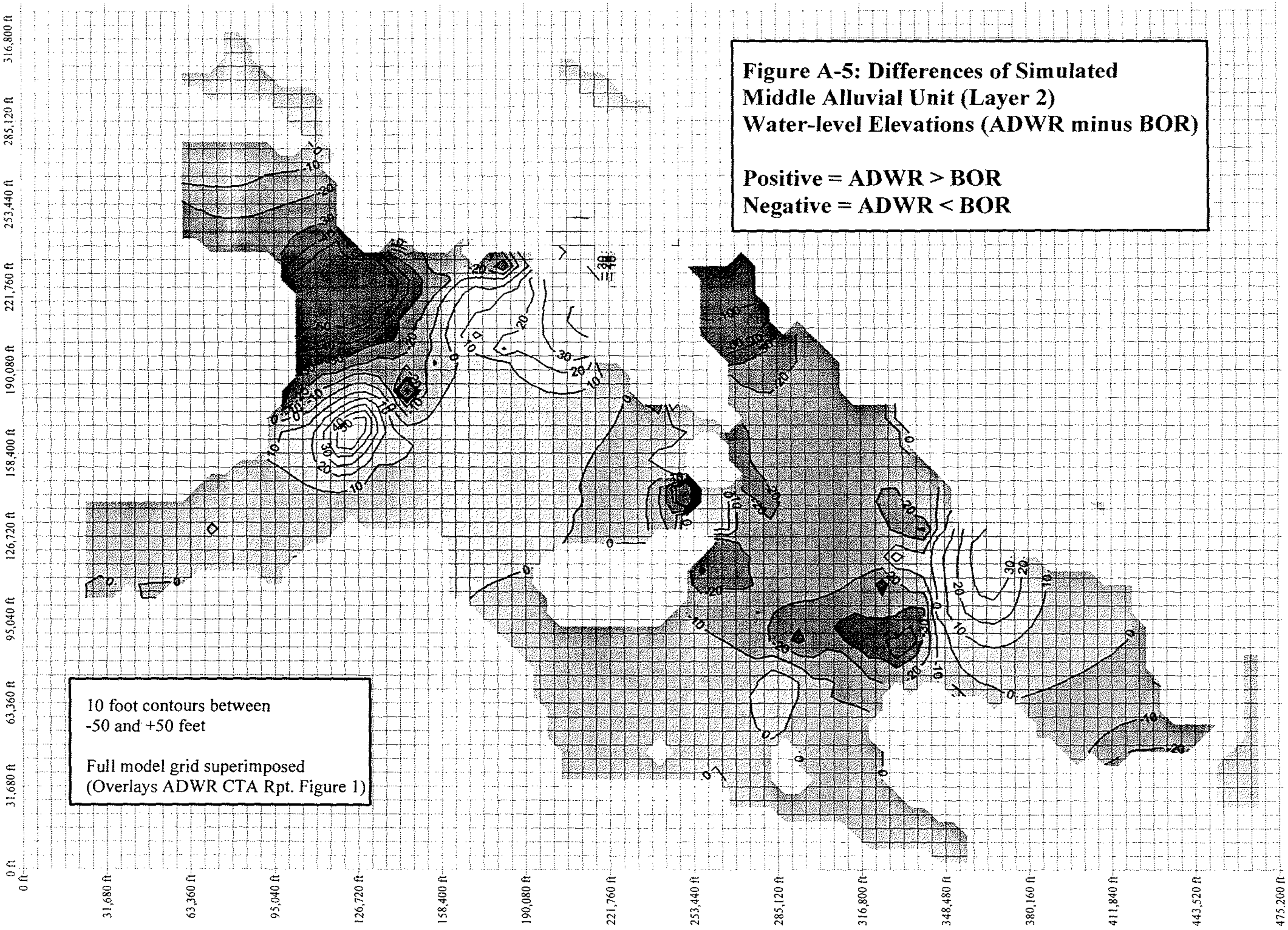

Figure A-5: Differences of Simulated Middle Alluvial Unit (Layer 2) Water-level Elevations (ADWR minus BOR)

Positive = ADWR > BOR
Negative = ADWR < BOR

10 foot contours between
-50 and +50 feet

Full model grid superimposed
(Overlays ADWR CTA Rpt. Figure 1)

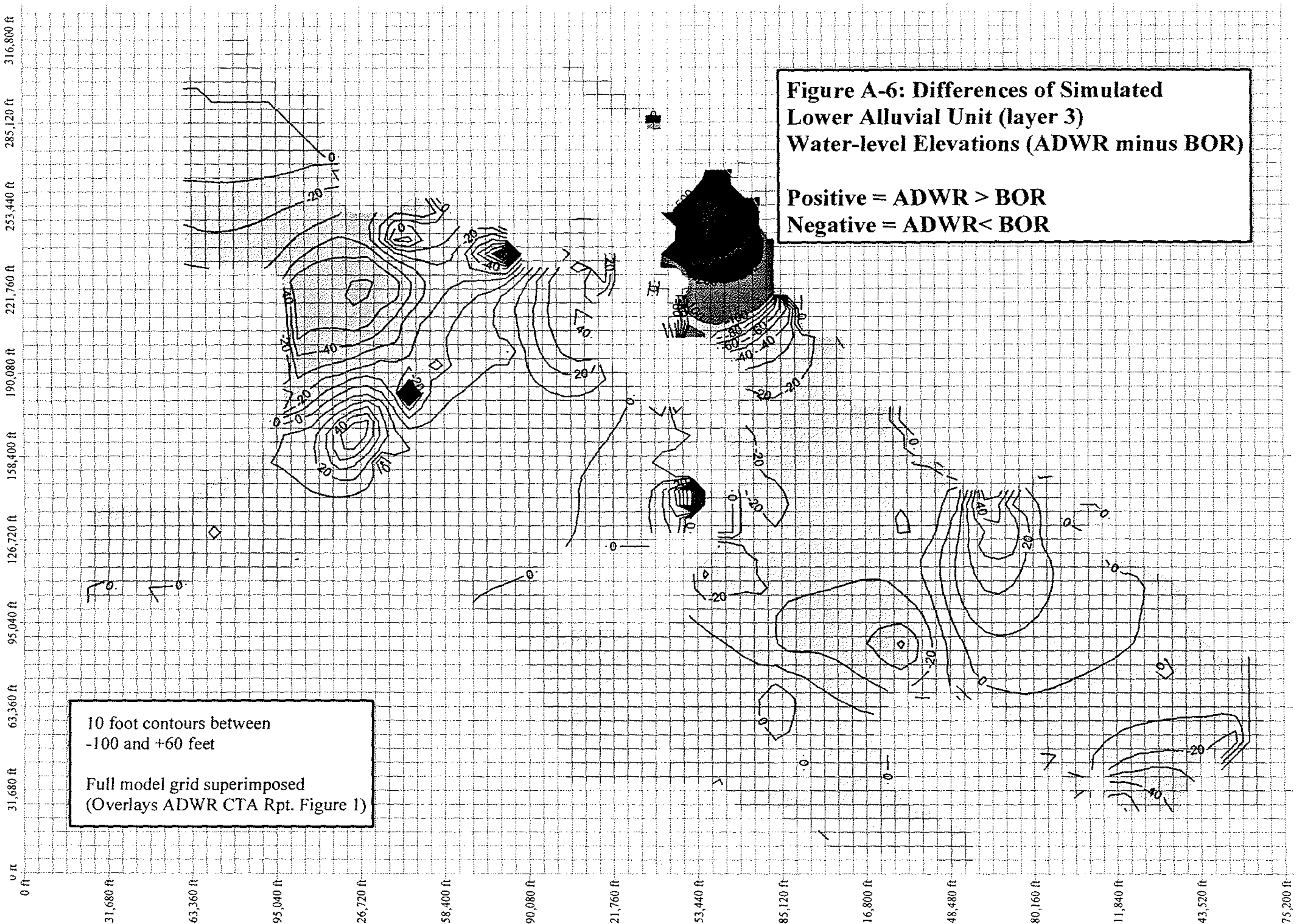

Figure A-6: Differences of Simulated Lower Alluvial Unit (layer 3) Water-level Elevations (ADWR minus BOR)

Positive = ADWR > BOR
Negative = ADWR< BOR

10 foot contours between
-100 and +60 feet

Full model grid superimposed
(Overlays ADWR CTA Rpt. Figure 1)

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Inspection of Figure A-4 indicates that the differences range in value between 0 and 10 feet over much of the UAU. Exceptions include three small areas of differences greater than 20 feet in ESRV and one area of differences greater than 20 feet in WSRV. The area of differences greater than 20 feet in WSRV is attributed to greater pumping rates applied by BOR in the LPSCO area compared to the ADWR-CTA pumping rates.

Inspection of Figure A-5 indicates that the differences range in value between 0 and 20 feet over much of the MAU. Exceptions include seven local areas of differences greater than 20 feet in ESRV, six local areas of differences greater than 20 feet in WSRV, and one area of differences greater than 20 feet where flow from ESRV joins the WSRV. Less pumping by BOR than ADWR results in the area of negative differences in a large area of the northwestern WSRV. An adjacent area of positive differences greater than 20 feet in WSRV is attributed to greater pumping rates applied by BOR in the LPSCO area compared to the ADWR-CTA pumping rates.

Inspection of Figure A-6 indicates that the differences are between 0 and 20 feet over much of the LAU. Exceptions include seven local areas of differences greater than 20 feet in ESRV, five local areas of differences greater than 20 feet in WSRV, and one area of difference greater than 20 feet where flow form ESRV joins the WSRV. Less pumping by BOR than ADWR results in the area of negative differences in a large area of the northwestern WSRV. An adjacent area of positive differences greater than 20 feet in WSRV is attributed to greater pumping rates applied by BOR in the LPSCO area compared to the ADWR-CTA pumping rates.

In summary, inspection of the water-level elevation differences confirms the conclusions developed earlier that the ADWR-CTA and BOR-CTA models are providing similar results. Lesser pumping rates provided by the BOR-CTA model result in less drawdown and greater build up in local areas. One area of large differences is in the far northern part of Phoenix, which is in ESRV and isolated from WSRV. This area is a primary example of BOR correcting pumping rates greater than total demand.

Selected Simulated Hydrographs

As a final comparison, locations were selected in the WSRV to monitor the changes in water-level elevations simulated by the two models. The locations of the hydrographs are shown on Figure A-3. The following locations were the selected:

1. Buckeye (general western outflow location in WSRV)
2. Between Avondale and Tolleson (general south-central location in WSRV)
3. Central Phoenix (general eastern inflow location in WSRV)
4. Laveen (general southern inflow location in WSRV)
5. Luke Sink (general central location in WSRV and historic pumping center)
6. North of the White Tank Mountains (general northern inflow location in WSRV)

Figure A-7 shows the hydrographs simulated in the UAU layer for the Buckeye, Avondale/Tolleson, Central Phoenix, and Laveen locations. The other locations (Luke Sink and North of the White Tank Mountains) are dewatered in the UAU of the SRV model. The only clearly recognizable difference is a greater drawdown in the Avondale/Tolleson area in the BOR-CTA after approximately 12 years of simulation. The greatest difference is approximately 10 feet. The noted differences are considered acceptable given that the hydrograph shapes are similar.

Figure A-8 shows the hydrographs simulated in the MAU for the six locations listed above. The difference in drawdown over time noted in the UAU near Avondale/Tolleson is also noted in the MAU. The BOR-CTA simulates more drawdown in the Luke Sink MAU between 14 and 35 years into the simulation when the ADWR-CTA catches up and then simulates greater drawdown. The ADWR-CTA simulates suddenly greater drawdown north of the White Tanks Mountains in the MAU after 32 years into simulation. The noted differences are considered acceptable given that the hydrograph shapes are similar.

Figure A-8 shows the hydrographs simulated in the LAU for the six locations listed above. The LAU hydrographs are visibly similar to those in the MAU (Figure A-8) and similar differences are noted. The noted differences are considered acceptable given that the hydrograph shapes are similar.

In summary, inspection of selected hydrographs in the WSRV indicates that the ADWR-CTA and BOR-CTA models are providing similar results with differences that are acceptable in magnitude for the WESTCAPS Groundwater Model project.

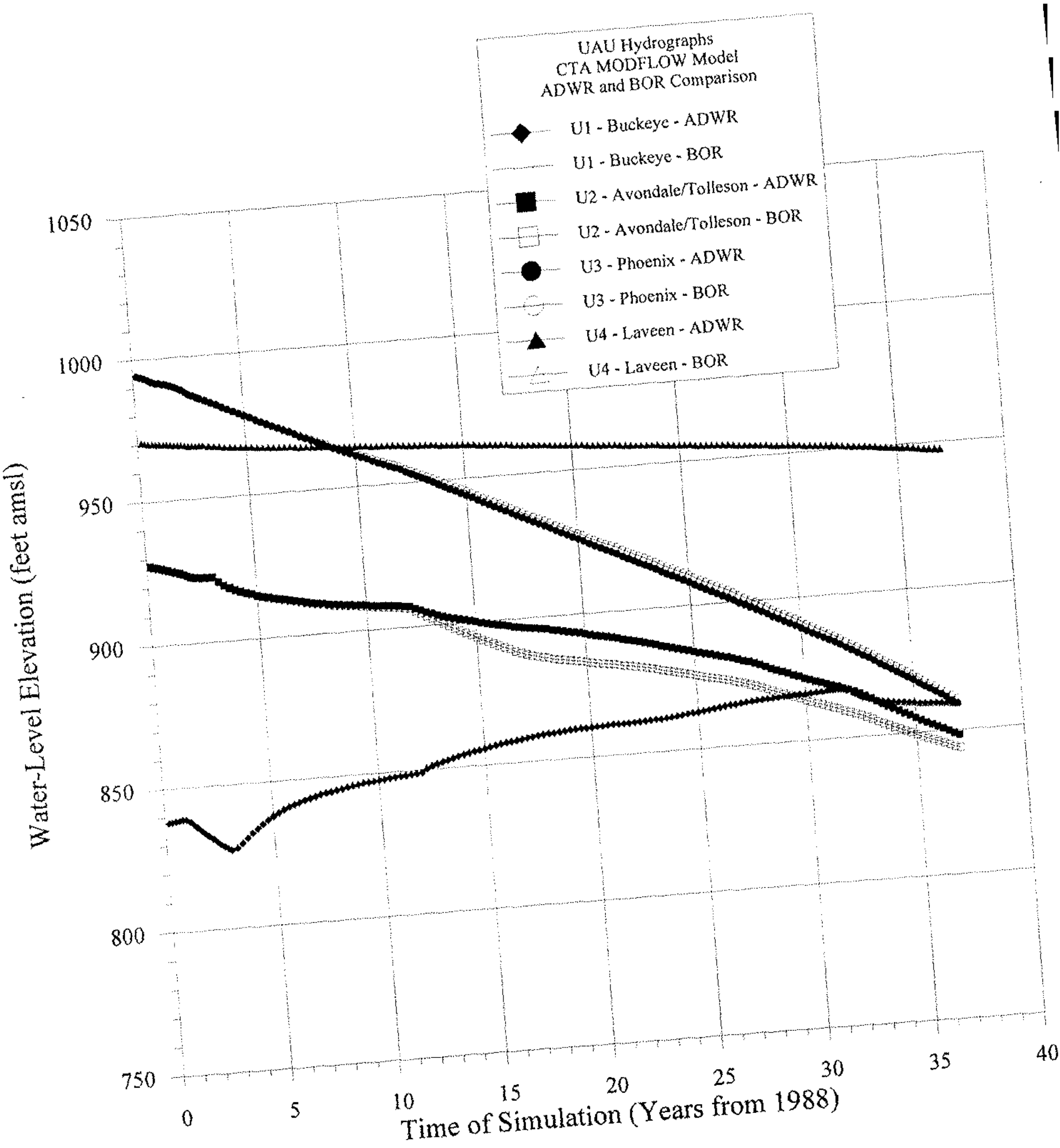

Figure A-7: Simulated Upper Alluvial Unit Hydrographs

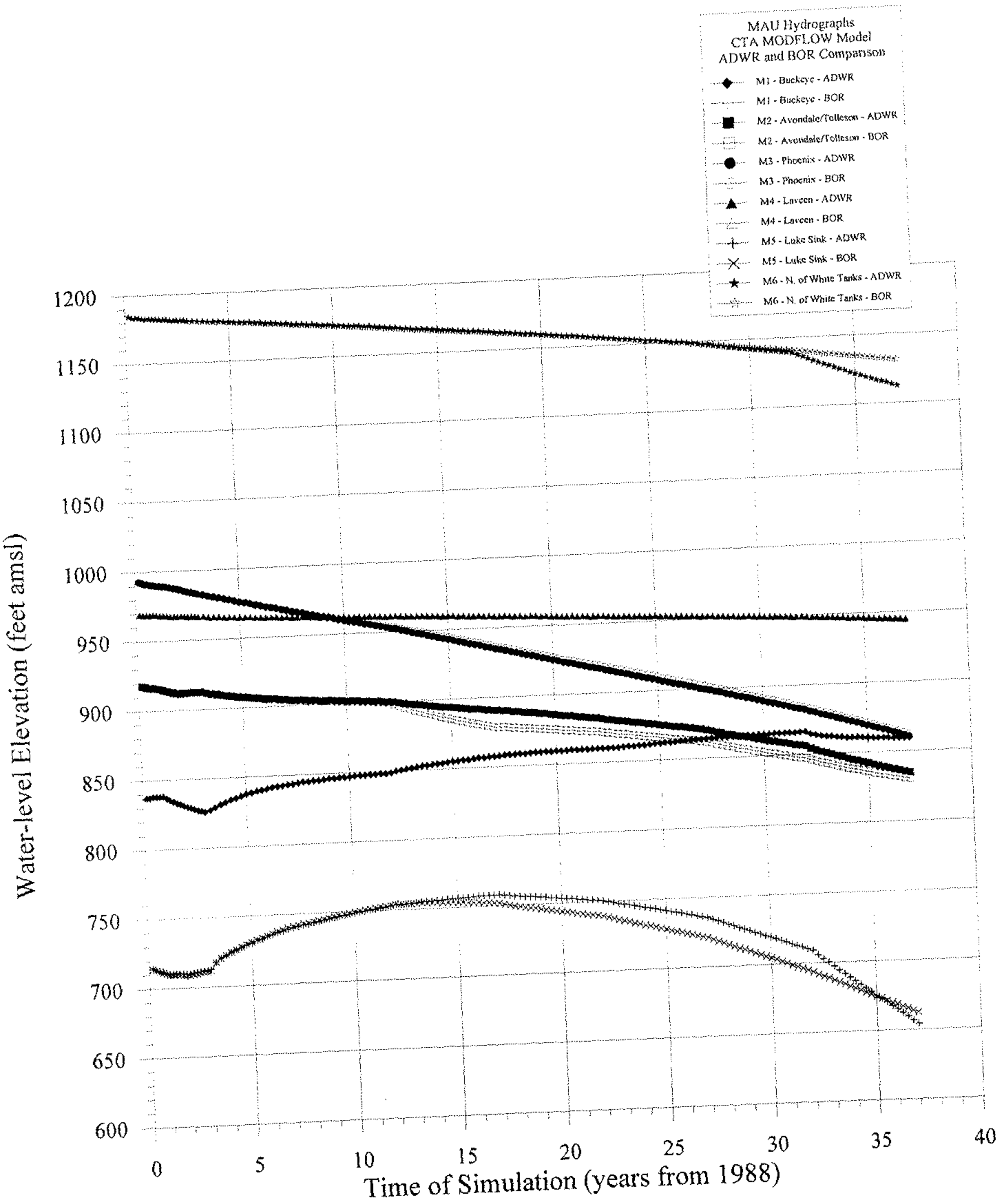

Figure A-8 Simulated Middle Alluvial Unit Hydrographs

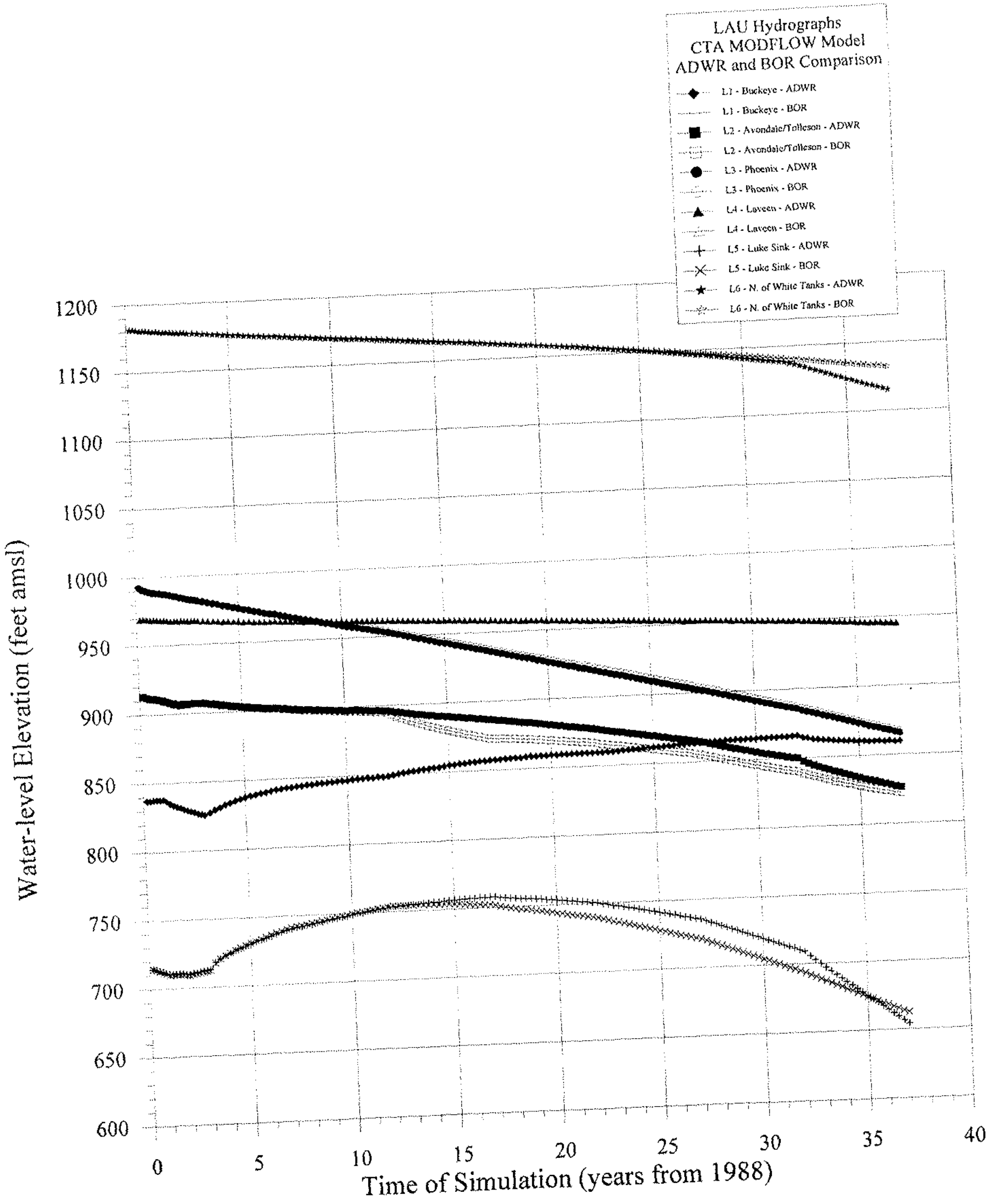

Figure A-9: Simulated Lower Alluvial Unit Hydrographs