CHAPTER 7

Evaluation of Basin Scale Improved Water Management Alternatives in the Lower Arkansas River Valley, Colorado

The *LAR GeoDSS* is applied to screening of improved water management alternatives in the LARV in Colorado from Pueblo Reservoir to the Colorado-Kansas State Line (Figure 1.1). The ultimate goals of the management alternatives are to maximize the net economic benefits of agricultural production and to improve water quality of the stream-aquifer system by reducing salinity, waterlogging, salt loads and concentrations in the stream-aquifer system and non-beneficial consumption of water; while maintaining water right entitlements and river compact agreements. The study uses a retrospective approach in which "what if" scenarios are used to compare the flows, concentrations and system storage under various management alternatives with the historical-calibrated baseline. The purpose is to quantify the expected relative improvements to the river system that are possible by applying these various alternatives, as well as ascertaining the feasibility of implementation in a complex, legally constrained system. The management alternatives are evaluated using the conjunctive surface and groundwater quantity and quality modeling tools presented in Chapter 6. As an initial approach to the alternative screening process, it is assumed that river basin water users are fully participating in the proposed management alternatives.

For these areas in the LARV where detailed groundwater modeling is unavailable a significant challenge is presented in evaluating the improved management alternatives. Figure 4.1 shows the current groundwater modeled area used in this case study, and the projected downstream modeled area where detailed groundwater modeling will be available in the near future for testing and improvement of the stream-aquifer modeling. In the non-modeled areas, the ANN-based stream-aquifer interaction module incorporated in the *LAR GeoDSS* applies learned-relationships between basin scale-measurable explanatory variables and the regional-scale stream-aquifer MODFLOW-MT3DMS modeled interaction. This procedure provides an approximation of the return flows and salt loadings to the tributaries and river, with predictions expected to increase in uncertainty with distance from the groundwater modeled region. Since the ANN has been trained to respond to system state changes during assessment of the management alternatives, the ANN is expected to predict deviations from a baseline prediction when simulating the management alternatives regardless of the baseline prediction error. These deviations can be used to evaluate the relative benefits associated with these alternatives. In addition, the ANN accommodates predicted changes in base flows in the Arkansas River and tributaries.

As presented in Chapter 6, the Arkansas River basin water quality calibration algorithm imposes restrictions that create discrepancies between the measured and the modeled salinity concentrations. The evaluation of alternatives is based on the simulated baseline concentrations rather than the historical measured concentrations. Since calibrated concentrations are used in the simulation of management alternatives, the relative comparison of changes in concentration is used as indicator of the benefits associated with each alternative.

Results of evaluation of the improved management alternatives are based on calibrated gains and losses computed for the baseline network. Therefore, the simulation of alternatives assumes that hydrologic and operational conditions present in the historical simulation scenarios are not altered by adjustments in the system operations. Since some of the management alternatives might cause changes in these gains and losses (e.g., irrigation surface runoff or canal operational flows), errors may be introduced in using the computed gains and losses. The *LAR GeoDSS* is utilized as decision support tool to evaluate the benefits and feasibility of the regional-scale management alternatives for a historical period, and it is assumed that this retrospective approach provides a reasonable framework for evaluation of improved management alternatives by reducing the impact of calibration and simulation errors in the analysis.

DESCRIPTION OF IMPROVED MANAGEMENT ALTERNATIVES

Four remediation alternatives and various combinations of these were evaluated at the regional-scale (Burkhalter 2005, Burkhalter and Gates 2005, 2006). The alternatives include increased irrigation efficiency, reduction in canal seepage, increase in groundwater pumping (vertical drainage), and installation of sub-surface drains. At the river basin scale, these alternatives are modeled as changes in water demands at the diversion points. The challenge in modeling the alternatives in the *LAR GeoDSS* is to calculate realistic reductions in historical water demands as a consequence of the simulated changes in system operations at the regional and field scales. These simulated reductions in diversions provide additional instream flows requiring decisions on appropriate allocation. Since the historical gains and losses computed during the network calibration are implemented in each simulation as high priority system sources and sinks, the reduction in diversions becomes additional water available to the surface system that should be allocated, disposed or stored. Each improved water management scenario establishes a target for combinations of increased irrigation efficiency, seepage reduction, and additional pumping alternatives that translate into a canal diversion reduction scenario. The goal is to consistently combine the diversion reduction components associated with each alternative such that system water demands reflect the combined effects of the simulated conditions.

Canal Seepage Reduction

For this analysis, it is assumed that the majority of seepage reduction in canals conveying water to the fields takes place as a consequence of canal lining or treatment measures, with small flow reductions due to other management strategies (e.g., irrigation induced aquifer recharge reduction). In this management alternative simulation, water diverted to the canal is to be reduced by an amount equal to the simulated reduction fraction of the baseline seepage loss. When a canal is hydraulically connected to the aquifer, the MODFLOW modeled seepage amount is affected by other management alternatives since changes in water table depth at the vicinity of the canal induce changes in the computed canal seepage. In this study, however, as an initial approximation, it is assumed that there are significant changes in the amounts of canal seepage only when explicit measures to reduce seepage are specified in the management alternative.

The volume of seepage from the canals in the modeled areas can be spatially determined from the MODFLOW output, but these volumes are not available for the non-modeled canals in the basin. Based on the regional groundwater model average conveyance efficiency (E_C) of 80% (Gates et al. 2002), the average channel loss coefficient ($\bar{s}$) for all canals in the LARV was assumed as:

$$\bar{s} = 1 - E_C = 1 - 0.80 = 0.20 \quad (7.1)$$

The canal seepage amount associated with a seepage reduction management scenario (*S'*) can be computed as a function of the baseline diversion (*D*), the seepage coefficient ($\bar{s}$) and the seepage reduction fraction (R_S)

$$S' = D'\bar{s}' = (D \cdot \bar{s})(1 - R_S) \quad (7.2)$$

where *D'* = the reduced diversion for the scenario and $\bar{s}'$ = the equivalent seepage factor for this modeled alternative that generates the expected reduced canal seepage amount (*S'*). Therefore, for this *LAR GeoDSS* stage, the baseline total canal seepage loss was approximated as 20% of the canal diversion.

The baseline average seepage loss coefficient ($\bar{s}$) is entered by the user in the data-model field *MOD_SeepCoef* belonging to the *Modsim_Demands* feature class. This value is used in the system simulation to calculate the baseline seepage and to reduce the seepage for the management alternatives accordingly. The calculated seepage is recorded into the MODSIM output file and is available for display though the *LAR GeoDSS* analysis tools.

Increased Irrigation Efficiency

Implementation of field-based irrigation induced aquifer recharge reduction at basin scale is based on calculations performed during the regional-scale groundwater simulation. A review of the regional-scale calculation is presented in this section along with the underlying principles for its basin scale implementation.

Regional Scale Groundwater Modeling Analysis

The regional-scale groundwater modeling approach (Gates et al. 2002, Burkhalter and Gates 2005) was analyzed to establish assumptions that adequately reflect the effects of implementing the regional-scale findings at a larger basin scale.

Irrigation Induced Aquifer Recharge Calculation

Areal aquifer recharge in the regional-scale model is calculated as a function of precipitation, groundwater pumping, crop water requirements and system irrigation efficiencies. Effective precipitation (p_e) over the modeled area is calculated as a fraction of total precipitation (p). If weekly precipitation is less than 50mm, 70% of the total precipitation is assumed to be the effective precipitation (30% surface runoff); otherwise, 50% of the total precipitation is assumed effective (50% surface runoff).

$$p_e = \left| \begin{array}{ll} 0.70p & \therefore If \;\; p < 50 \, {}^{mm}\!/\!_{week} \\ 0.50p & \therefore If \;\; p \geq 50 \, {}^{mm}\!/\!_{week} \end{array} \right. \tag{7.2}$$

Average Irrigation Application Efficiency

For each canal command area, the equivalent diverted (D) and pumped (P) depths per irrigated area are summarized in mm per week. The weekly required evapo-transpiration per canal command area (ET) in mm is estimated using a weighted average of the calculated evapo-transpiration of the crop. Average irrigation efficiency ($\overline{E}_I$) is calculated as the ratio of the total water required (factoring out the effective precipitation) to the total water diverted and pumped from wells.

$$\overline{E}_I = \frac{ET - p_e}{D + P} \tag{7.3}$$

As mentioned above, average conveyance efficiency ($\overline{E}_C$) for canals in the command area is assumed as 0.80. Average application efficiency ($\overline{E}_A$) accounts for only water available at the field to quantify the effectiveness in the application of the water (i.e., farmer activities). The average application efficiency is defined as:

$$\overline{E}_A = \frac{\overline{E}_I}{\overline{E}_C} \tag{7.4}$$

Application efficiency values for each field in a canal command area were generated from a truncated normal distribution with a mean equal to the average application efficiency. The minimum and maximum values of the truncated application efficiency are 0.15 and 0.85 respectively. Average application efficiency for Burkhalter and Gates (2005) modeled area located upstream of John Martin reservoir was calculated using the series of efficiencies from all the fields, replacing outliers with the maximum and minimum allowed values. The average baseline application efficiency for the modeled area was computed as 0.52.

Aquifer Recharge Amount by Field

The aquifer recharge amount was calculated for each field in the command areas. Each field was assigned a random number and the corresponding field application efficiency (e_A) was assigned to each field accordingly (from the truncated normal distribution with average $\overline{E}_A$). The required irrigation depth (h_I) per field was calculated as:

$$h_I = h_{ET} - p_e \tag{7.5}$$

where h_{ET} = total evapo-transpiration depth in the field as a function of the crop and its development stage.

The field application amount depth (h_a) was calculated for fields with positive values of h_I (i.e., when effective precipitation was smaller than the required irrigation depth) as:

$$h_a = \frac{h_I}{e_A} \tag{7.6}$$

The deep-percolation fraction (*DP*) in the regional-scale groundwater modeling was assumed as a fraction of the total irrigation loss (i.e., the applied irrigation depth in excess of the required depth). An assumed uniform DP fraction of 0.7 was used to compute the portion of excess water percolating below the root zone. This value was based on field data collected in the Colorado's South Platte River Valley (Walter 1995). The field leaching fraction (*lf*) is calculated as:

$$lf = DP(1 - e_A) \tag{7.7}$$

Based on the average field application efficiency for all canals in the regional-scale groundwater modeled area, the average leaching factor in the modeled area is adopted as:

$$lf = 0.7(1 - 0.52) = 0.34 \tag{7.8}$$

and field recharge depth (h_R) is approximated as:

$$h_R = lf\,(h_a + p_e) = DP(1 - e_A)\left(\frac{h_I}{e_A} + p_e\right) \tag{7.9}$$

substituting Equation 7.5 in this equation gives:

$$h_R = DP(1 - e_A)\left(\frac{h_E - p_e}{e_A} + p_e\right) \tag{7.10}$$

In terms of the water depth applied to the fields:

$$h_R = DP(1-e_A)(d_f + p_f + p_e) \tag{7.11}$$

where d_f = proportional surface water diversion depth applied to each field and p_f = pumping equivalent depth of water applied to each field. The adjusted recharge to the groundwater table is calculated assuming irrigation scheduling and water availability for each week.

Reductions in h_R by increased irrigation efficiency not only contribute to lowering the water table, but also have an effect on the leaching of salts from the root zone to the water table (Burkhalter and Gates 2006). This effect is accounted for in the unsaturated zone module of the MODFLOW-MT3DMS model used to calibrate the ANN module.

Areal Recharge Reduction Implementation at Regional-Scale

Since the main source of areal recharge reduction is increased irrigation efficiency, aquifer recharge reduction was simulated only during the irrigation season. Modeled recharge for the improved management scenarios should not significantly change during the off season, where precipitation is the primary source of recharge. Figure 7.1 illustrates an example of the weekly total aquifer recharge for the Burkhalter and Gates (2005) modeled area as an input to MODFLOW-MT3DMS for alternative *Rech80Seep90Drain50*, which implements 80% areal recharge reduction (through increased irrigation efficiency), 90% seepage reduction and subsurface drainage with density of 50 (i.e., 50 m spacing of 2.5 m-deep sub-surface horizontal relief drains installed in fields with water table depth of less than 2.0 m).

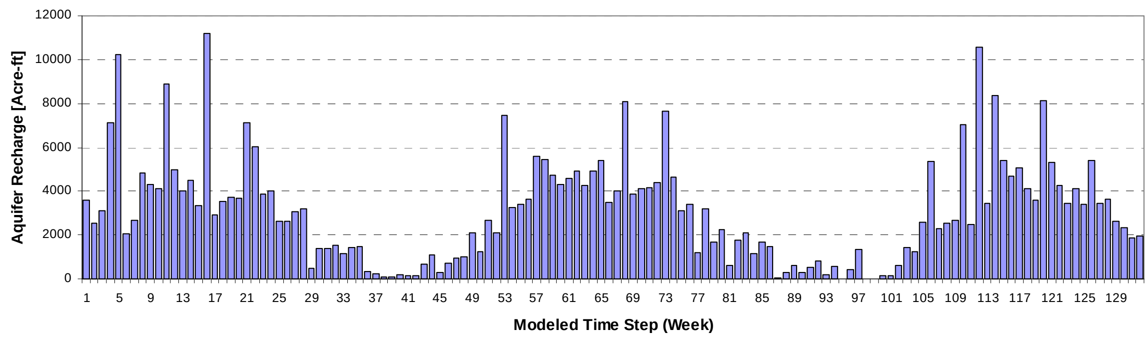

Figure 7.1 – Example of the total aquifer recharge volume simulated in MODFLOW

LAR GeoDSS Aquifer Areal Recharge Modeling

The areal aquifer recharge amount is a function of water available at the fields for irrigation. Part of the total water diverted (D) to a canal per time step seeps out while flow is conveyed to the farm delivery gates. Therefore, only a portion of the diverted water (*F*) is available to irrigate the fields, which is approximated as:

$$F = D - D \cdot \bar{s} \tag{7.12}$$

Ultimately, areal recharge to the aquifer is a fraction of the total available water at the field, which includes delivered surface water, precipitation and pumped water. For practical purposes, recharge reduction in *LAR GeoDSS* is assumed to apply only to the delivered surface water available at the fields. Therefore, reduction of water diverted to a canal is based on the portion of the baseline areal aquifer recharge that is reduced under that canal. The fraction of *F* representing deep percolation was computed using the application efficiency and the average leaching fraction (*lf*):

$$R_d = F \cdot (lf) = F \cdot \left(DP\left(1 - \bar{E}_A\right)\right) = 0.34 \cdot F \tag{7.13}$$

where R_d = the amount of water available at the fields that recharges the groundwater aquifer as deep percolation. Start and End dates for the irrigating season are entered by the user in the *LAR GeoDSS Simulation Scenario Manager* interface, which trigger the simulation of areal aquifer recharge reduction for those time steps that fall between them. Default dates for the irrigating season are set to April 1st to October 31st.

Pumping Increase

Additional groundwater pumping was evaluated as an alternative intervention to lower saline water table elevations where historical pumping is increased by an alternative-specified factor to simulate a vertical drainage situation. In this simulation, additional pumped water was assumed returned to the river system during the same time step using the surface drainage network. This condition was simulated in the *LAR GeoDSS* by evenly distributing the additional water pumped over all non-storage river nodes in the grouping area. Each of the non-storage river nodes was set with a local inflow equal to its corresponding fraction of the additional pumping. The concentration of the non-storage node inflow was set to the computed groundwater concentration. The amounts and concentrations were available in the *LAR GeoDSS* output display under the non-storage node local inflow.

In addition to vertical drainage, an agricultural water exchange situation was implemented in the *LAR GeoDSS* as a water use option for this scenario. In this case, the extra pumped water (ΔP) was used to irrigate crops by exchanging it for available surface water that was not diverted at the canal head gate. Therefore, the diversion to the canals was accordingly reduced in this case. Water pumped in this scenario was assumed to directly replace a portion of the surface water available to the fields (F). Water available to the fields in the management alternative simulation F' is calculated as:

$$F' = \left(D - D \cdot \bar{s}\right) - \Delta P \tag{7.14}$$

The percentage of pumping increase from the baseline (I_p) was entered by the user in the *LAR GeoDSS Simulation Scenario Manager* interface. For example, if a value of I_p = 20 is entered in the GUI, it is interpreted as a resulting pumpage of 120% of the baseline pumping.

Subsurface Drainage Improvement

This management alternative improves subsurface drainage by installing horizontal perforated pipe drainage systems at various spacings and at a uniform drain depth of 2.5 m (8.2 ft) in irrigated fields with water table depth less than 2.0 m (6.6ft). It was assumed that this scenario does not interfere with canal diversions in the system and that the irrigation water amount applied to the fields remains relatively unchanged. Subsurface drains capture groundwater flow, thereby lowering the saline water table and increasing the rates of return flow to the surface water system. Water quality is potentially improved slightly since dissolution of salts in the porous media is reduced due to transit of flows in the drains rather than through the subsurface. Volumes drained through the improved drainage system were available in the regional modeled area but unavailable every where else in the basin. An additional model would have been required to predict basin-wide drained volumes; therefore, simulations of these management alternatives in the *LAR GeoDSS* reflect only the corresponding changes in the groundwater return flows. In other words, drainage effluent was not routed back to the river in the current version of the model. As a result of this assumption, it is expected that the results of this simulation indicate the minimum improvement achieved with the implementation of subsurface drainage. An indicator was used as an ANN explanatory variable to trigger the effect of this management scenario in the ANN stream-aquifer interaction modeling.

Alternatives Modeling Methodology and Implementation

The *LAR GeoDSS* modeling system manages additional water generated from the alternatives resulting in reductions in water demand. Water is managed to satisfy historical water demands adjusted by the reduced water demands within the specified reservoir operation rules. The Geo-MODSIM simulation model operates the system by storing water up to the specified target and releasing flows to meet system water demands by accommodating the operations to changes in return flow patterns and timing.

LAR GeoDSS Simulation Variables

The *LAR GeoDSS Simulation Scenario Manager* adjusts system demands and equivalent seepage coefficients to reflect the simulated management alternative. Since multiple management alternatives can be applied simultaneously, the interrelationship between them must be considered when implementing the water demand adjustments. In this section, a set of equations was developed to compute canal diversion reductions and seepage coefficients for the combined impacts of the alternatives. The most general case was the combination of three management scenarios (i.e., irrigation-induced areal recharge reduction, seepage reduction, and additional pumping). In this case, reduced volume available to the fields (F’) is calculated as:

$$F' = D' - D'\overline{s}' \tag{7.15}$$

where D'= the adjusted water demand at the canal head gate and $\bar{s}'$ the adjusted average canal seepage loss coefficient. Water available to the fields for the combined recharge and pumping scenarios can be calculated as:

$$F' = F - F \cdot lf \cdot R_R - \Delta P = F \cdot (1 - lf \cdot R_R) - \Delta P \tag{7.16}$$

Substituting Equation 7.12 into Equation 7.16 and combining term gives:

$$F' = D(1-\bar{s})(1 - lf \cdot R_R) - \Delta P \tag{7.17}$$

substituting Equation 7.15 into Equation 7.17 gives:

$$D' - D'\bar{s}' = D(1-\bar{s})(1 - lf \cdot R_R) - \Delta P \tag{7.18}$$

From Equation 7.2, the simulation scenario average seepage coefficient can be expressed as:

$$\bar{s}' = \frac{D\bar{s}(1-R_S)}{D'} \tag{7.19}$$

substituting Equation 7.19 into Equation 7.18 yields:

$$D' - D'\left(\frac{D\bar{s}(1-R_S)}{D'}\right) = D' - D\bar{s}(1-R_S) = D(1-\bar{s})(1 - lf \cdot R_R) - \Delta P \tag{7.20}$$

Assuming reduced diversion D' is computed as the baseline diversion minus an adjustment term (ΔD), Equation 7.20 is written as:

$$D - \Delta D = D\bar{s}(1-R_S) + D(1-\bar{s})(1 - lf \cdot R_R) - \Delta P$$

or

$$\Delta D = D - D\bar{s}(1-R_S) - D(1-\bar{s})(1 - lf \cdot R_R) + \Delta P$$

$$= D(\bar{s}R_S + lf \cdot R_R(1-\bar{s})) + \Delta P \tag{7.21}$$

Equation 7.19 can be rewritten as:

$$\bar{s}' = \frac{D\bar{s}(1 - R_S)}{D - \Delta D} = \frac{D\bar{s}(1 - R_S)}{D - \Delta D} \tag{7.22}$$

substituting Equation 7.22 in Equation 7.21 gives

$$\bar{s}' = \frac{D\bar{s}(1 - R_S)}{D - \left(D\left(\bar{s}R_S + lf \cdot R_R(1 - \bar{s})\right) + \Delta P\right)} \tag{7.23}$$

Equations 7.21 and 7.23 calculate the canal diversion reduction and equivalent seepage coefficient as a function of the management alternative reduction coefficients and system characteristics such as seepage coefficients and irrigation application efficiency. Details on the implementation of the diversion reductions in *LAR GeoDSS* are available in Appendix VI – *Management Alternative Demand Reduction*.

Stream-Aquifer Interaction

The ANN-based stream-aquifer interaction modeling required computation of several explanatory variables as a function of the Geo-MODSIM modeling results. The simulation of various management alternatives required modification of system characteristics and operations that should be reflected in the explanatory variables for effective ANN training, and simulation. For this purpose, the ANN "development in passes" approach (introduced in Chapter 4 – *Training in Passes*) was adopted for the *LAR GeoDSS*. Initially, in the first pass, the management alternatives were simulated without explicit stream-aquifer modeling using a calibration network to provide local gains and losses based on measured flows. These initial simulations implemented water demand reductions to accurately model changes in basin conditions according to each management scenario, and two reservoir operation scenarios. The ANN training dataset was constructed using these simulation results. In the second pass, stream-aquifer interaction modeling in the *LAR GeoDSS* was based on the trained ANN using explanatory variables computed from the first pass improved water management scenarios to reduce the impact on the prediction and to improve convergence. Using the first pass Geo-MODSIM results to compute the explanatory variables assumed that the flows and demands do not change significantly between the first and second pass solutions. A more refined training dataset can be developed from the second pass simulations to further refine the ANN training. The results presented herein correspond to the third pass, since low sensitivity and small variations in flows and diversions were detected with respect to the second pass.

Reservoir Operational modes

Reservoir system operations were an important element when analyzing management alternatives according to water quality impacts. This was documented by Willey et al. (1996) while applying HEC-5Q to the Columbia River system and other large integrated reservoir systems in the U.S. The two reservoir operating modes introduced in Chapter 6 were used in this management alternatives analysis.

Reservoir operation under Mode A set the storage targets to the historical measured volumes for simulating situations where no additional storage was committed to the implementation of the management alternatives. In this case, non-diverted water can be stored only to replenish historically stored water. Otherwise, this water continued downstream and if not used in the same time step to meet water demands within Colorado, was conveyed to Kansas. Although this operational mode requires minimum adjustments in reservoir operations for implementation of management alternatives, the inability to store and release the non-diverted flow increases the risk of violating water rights decrees and failing to comply with the Arkansas River Compact agreement with Kansas when the non-diverted water made available in the same time step cannot over come the impact of changes in return flow patterns.

The Mode B reservoir operations used balancing layers or zones in the reservoir so as to satisfy the Arkansas River Compact and release water to make up for reductions in irrigation return flows. Implementation of this mode is potentially more challenging since it could require amendments to the current storage water laws, such as creating a separate account in John Martin Reservoir to store non-diverted water rather than distributing that water within the River compact accounts according to the current allocation percentages.

MANAGEMENT ALTERNATIVE COMPARISON AND ANALYSIS

The simulated water management alternatives to improve the agro-ecological conditions in the basin were defined based on the previous regional-scale study (Burkhalter 2005). Table 7.1 provides a summary of the alternative names and descriptions, including a new alternative not modeled in Burkhalter (2005). These alternatives were designed to reduce soil and water salinity in order to improve crop yields in the basin, protect the lands from irreparable salinization, reduce non-beneficial water consumption on naturally-vegetated and fallow fields, and improve the water quality in the river. These alternatives include efficiency improvements at field scale, improvements to the conveyance system to reduce seepage, and groundwater pumping changes. Unfortunately, under Colorado water law, the use of the water “saved” by these improvements is limited. This analysis assumed that additional flows made available as a result of implementation of these alternatives could not be used for irrigating more land or additional crops. Water savings produced by the alternatives were not diverted by the water user and remained in the river system to support the alternative implementation. Water that was not diverted and remained in the surface system had a lower TDS concentration than that same water, had it been applied to the fields and returned later to the system through the stream-aquifer interaction process after working its way through geologic formations with potentially soluble salt deposits.

Table 7.1 – Simulated Management Alternative Summary

Alternative Name	Description	Alternative Name	Description
Baseline	Actual Historical Conditions	Pump200	Increase in pumping rates by 200%
Seep70	Reduction of seepage rates by 70% over full length of all Canals	Seep90Highline	Reduction of seepage rates by 90% over Highline Canal only
Seep50	Reduction of seepage rates by 50% over full length of all Canals	Seep90Otero	Reduction of seepage rates by 90% over Otero Canal only
Seep90All	Reduction of seepage rates by 90% over full length of all Canals	Seep90Holbrook	Reduction of seepage rates by 90% over Holbrook Canal only
Rech90	Reduction of recharge rates by 90%	Seep90FtLyon	Reduction of seepage rates by 90% over Fort Lyon Canal only
Rech80	Reduction of recharge rates by 80%	Seep90Catlin	Reduction of seepage rates by 90% over Catlin Canal only
Rech70	Reduction of recharge rates by 70%	Seep90Lined20	Reduction of seepage rates by 90% over targeted 20% length of all Canals
Rech60	Reduction of recharge rates by 60%	Seep50Drain100	Combination of alternatives
Rech50	Reduction of recharge rates by 50%	Rech80Seep90Drain50	Combination of alternatives
Rech40	Reduction of recharge rates by 40%	Rech80Seep90	Combination of alternatives
Rech30	Reduction of recharge rates by 30%	Rech80Drain50	Combination of alternatives
Rech20	Reduction of recharge rates by 20%	Rech50Seep90	Combination of alternatives
Rech10	Reduction of recharge rates by 10%	Rech30Seep50	Combination of alternatives
Drain50	Installation of horizontal drains over select fields at 50 m spacing	Rech30Drain100	Combination of alternatives
Drain75	Installation of horizontal drains over select fields at 75 m spacing	Rech30Seep50Drain100	Combination of alternatives
Drain100	Installation of horizontal drains over select fields at 100 m spacing	Rech50Drain50	Combination of alternatives
Drain150	Installation of horizontal drains over select fields at 150 m spacing	Seep90Drain50	Combination of alternatives
		Rech50Seep90Drain50	Combination of alternatives
Seep90RockyFd	Reduction of seepage rates by 90% over Rocky Ford Canal only	New_Rech50Seep50	New Combination for basin-scale analysis

Criteria for Evaluation of Alternatives

Basin-scale performance of the management alternatives was evaluated based on several aspects of the simulation: (1) water allocation and shortages, (2) river water quality, (3) reservoir storage and operations, (4) stream-aquifer interaction, and (5) reservoir water quality transport.

Water Allocation and Shortages

Simulation of the management alternative is feasible if all water demands are satisfied since this implies that the solution is in compliance with Colorado water rights. The management alternative analysis checked for water shortages in the simulated results so as to insure that all water use demands were completely satisfied.

Reservoirs Storage and Operation

The reservoir storage is analyzed during the management alternative evaluation in both weekly and end-of-period fashions. Storage change with respect to the historical storage indicates alterations to the current operation policy that may be needed and also indicates potential for environmental benefits from additional storage, when water generated by the improved management alternatives stored in the reservoir is released during periods of high concentrations.

Arkansas River Compact Compliance

An additional check in the water allocation for the management alternative simulation was the water allocated to Kansas since water management alternative solutions that provided at least historical flows were assumed to comply with the Arkansas River Compact.

Stream-Aquifer Interaction

Changes in stream-aquifer interaction associated with the management alternatives are an important aspect to be analyzed since the nature of the alternatives implies changes in return flows and salt loadings. Altering historical dynamics of the aquifer requires changes in system operations to satisfy water demands and can cause shortages that need to be quantified in order to compare among alternatives and to determine their feasibility.

River Water Quality

An indicator used for analyzing the basin-wide water concentration changes due to implementation of the management alternatives is the average TDS concentration at the location of all canal diversions from the river. This average captures the overall improvement in the river water quality that is diverted for beneficial use.

John Martin Reservoir Salt Transport

Reservoir salt transport is an important component of the management alternative analysis since it interrupts the sequential calculation of TDS concentration in the river basin by using a prediction of the complex processes occurring in John Martin Reservoir. The prediction of concentration at the reservoir outlet dictates starting concentrations for a second set of sequential calculations in the lower part of the modeled basin. The transport analysis strategy computes a transport coefficient (T_r) as:

$$T_r = \frac{\sum Mass_{out}}{\sum Mass_{in}} \tag{7.24}$$

where $Mass_{out}$ = salt mass leaving the reservoir and $Mass_{in}$= salt mass entering the reservoir. This factor indicates an overall concentration/dilution process of flows passing through the reservoir. Based on the baseline simulation indicators (Table 6.20), the transport coefficient in reservoir operations under Mode A (historical) = 1.27, which indicates an overall solute concentration increase through the reservoir. For reservoir operations under Mode B, changes in the system operation and corresponding water quantity and quality calibration increased T_r to 1.50 in this baseline simulation. In this case, changes in the inflow time sequence and the Arkansas River inflow concentration created a prediction with higher salt loadings in the reservoir release.

Alternatives Performance Comparison

The *LAR GeoDSS Simulation Scenario Analysis* tool was used to process the results of the alternatives to compare performance by using the aforementioned analysis criteria. The summary and analysis was categorized by reservoir operational mode, with analysis of overall performance evaluated using total simulated amounts and average concentrations. Detail system performance per time step is available in Appendix VI – *Management Alternatives Detailed Analysis*.

Reservoir Operational Mode A

Water Allocation and Shortages for Operational Mode A

The satisfaction of water demands was the first aspect of the management alternatives to be analyzed. The water demands were reduced from the historical diversions to reflect the calculated impact of the various management alternative characteristics as presented in the section *LAR GeoDSS Simulation Variables*. Figure 7.2 shows the computed-total water demand and the corresponding total canal loss for the simulated alternatives, which was a function of the water diverted. The alternatives are sorted in descending order of total water demand.

Demand shortages occurred when the management alternative produced less available water to the system for satisfying the adjusted demands. These shortages in the simulated alternatives indicate that there was insufficient available water in the system to meet water demands. Shortages occurred due to reduced return flows computed in the stream-aquifer interaction modeling and due to exhaustion of storage water and non-diverted water. Figure 7.3 shows the total simulated water shortages for the management alternatives. No water shortages were necessary to guarantee the appropriate water rights allocation.

Therefore, failing to provide the computed water demands made the alternative infeasible under the current reservoir operational mode. Small shortages were revealed in many alternatives, indicating only minor violations to the water rights. Only *Pump200*, *Seep90Catlin*, *Seep90Highline* and *Seep90FtLyon* alternatives had no water shortages. At this stage in the analysis, alternatives with significant shortages were discarded since their implementation was considered infeasible. Table 7.2 lists the infeasible alternatives due significant shortages resulting in violation of the users' water rights.

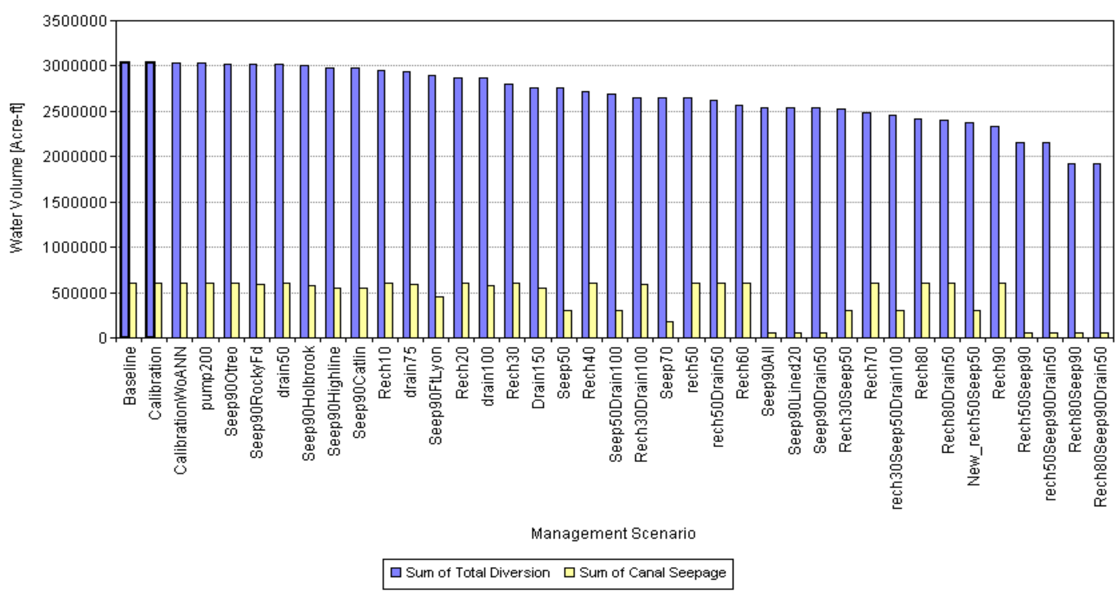

Figure 7.2 – Management alternatives water demands and canal loss for operational mode A

Table 7.2 – Infeasible Management Alternatives Due to Water Shortages in Operational mode A

Alternative Name	Water Shortage [Acre-ft]
Drain50	13269
Rech50Drain50	36978
Rech80Drain50	41278
Seep50Drain100	72202
Drain75	89013
Rech30Seep50Drain100	89265
Drain100	154491
Rech30Drain100	155780
Drain150	268037

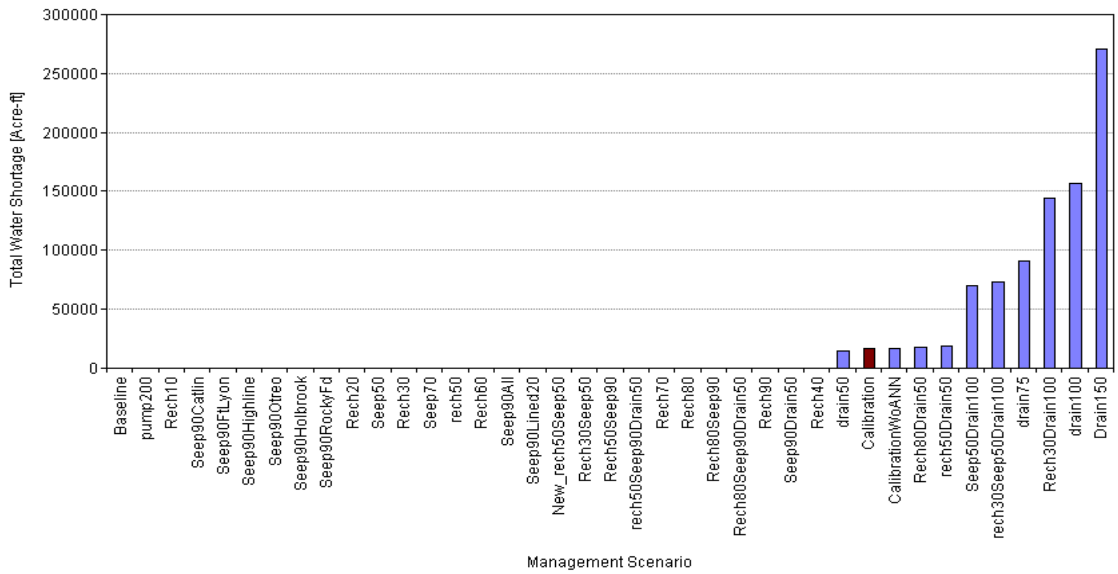

Figure 7.3 – Management alternatives water demand shortage for operational mode A

Reservoir Storage and Operation for Operational Mode A

In this reservoir operational mode, the additional downstream river flows caused by the alternatives were used to replace reductions in return flows and to replenish reservoir volumes to historical levels. The ability to replenish reservoir storage and maintain the system end-of-simulation storage was an indicator of the sustainability of the alternative over the long run. The modeling system in this mode used historically stored water to meet water obligations, but it was set up to recover the water as soon as possible. During simulation, a reservoir storage that was lower than the historical storage volume indicates that additional water was requested and "borrowed" from the reservoirs (see detailed plots of results in Appendix VI). The length and magnitude of the "borrowing" water operation was an indicator of the relative degree of change of the current reservoir operational polices for a successful alternative implementation.

The reservoir storage was summarized for the simulated alternatives as the end-of-simulation system storage, which can be checked against the baseline end-of-simulation system storage (Figure 7.4). Even though this operational mode was restrictive in the use of additional storage, the lack of storage at the end of the simulation represents a situation that most likely will cause difficulties in the implementation of the alternative under this system operational mode. The closer the operation is to the historical volumes, the less alteration to the current reservoir operation is required for implementation of the alternative. Under the highly constraining water laws in the LARV, requiring less modification to the current operation facilitates implementation of the alternative. Alternatives with no end-of-simulation storage were the same ones that exhibit significant shortages (Table 7.2). Ideally, storage at the end of the simulation should be the same as its counterpart in the baseline simulation to indicate that in the long run no special reservoir operation is necessary for implementation of the alternative. Alternatives with end-of-simulation storage lower than historical indicate that the alternative implementation might still be possible if additional storage is allowed.

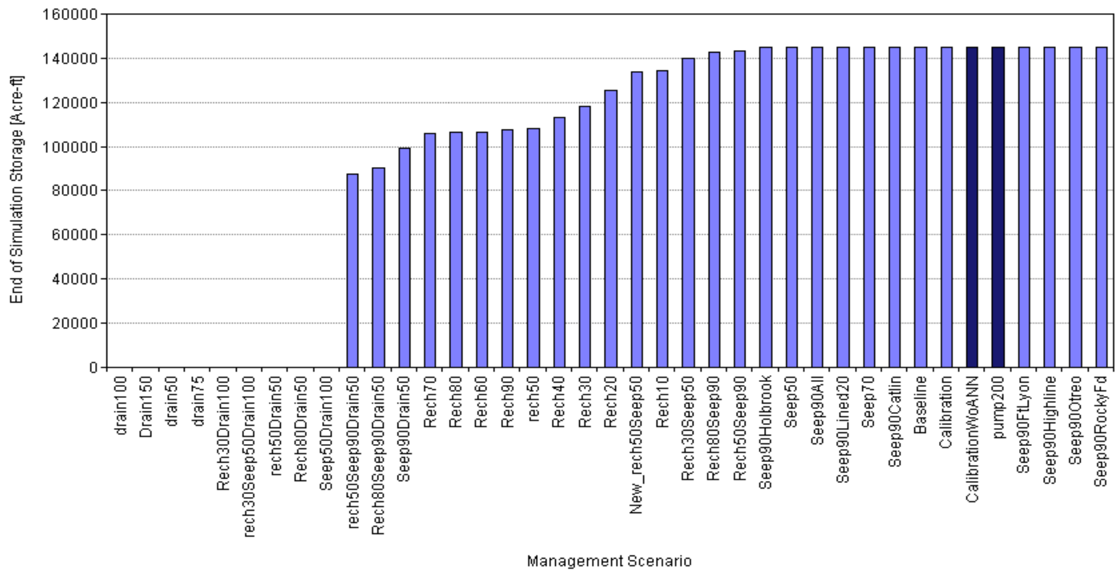

Figure 7.4 – Management alternatives end-of-simulation system storage in operational mode A

<u>Arkansas River Compact Compliance for Operational Mode A</u>

Management alternatives were required to at least duplicate the baseline historical flows to the Kansas account of the Arkansas River Compact, thereby assuring compliance with the Arkansas River Compact. It was assumed that Colorado was in compliance with the compact during the period 1999-2001 selected for the simulation of the alternatives. Colorado water users (Water District 67) that received water from the compact were assumed to participate in the management alternative program. Therefore, they were assumed to allow the non-diverted water to be used in the alternative implementation according to the reservoir operational mode. Figure 7.5 shows the simulated flows to Kansas for each of the management alternatives. Five alternatives failed to provide the water requirements to Kansas, including: *Drain150*, *Rech30Drain100*, *Drain100*, *Rech30Seep50Drain100*, and *Seep50Drain100*.

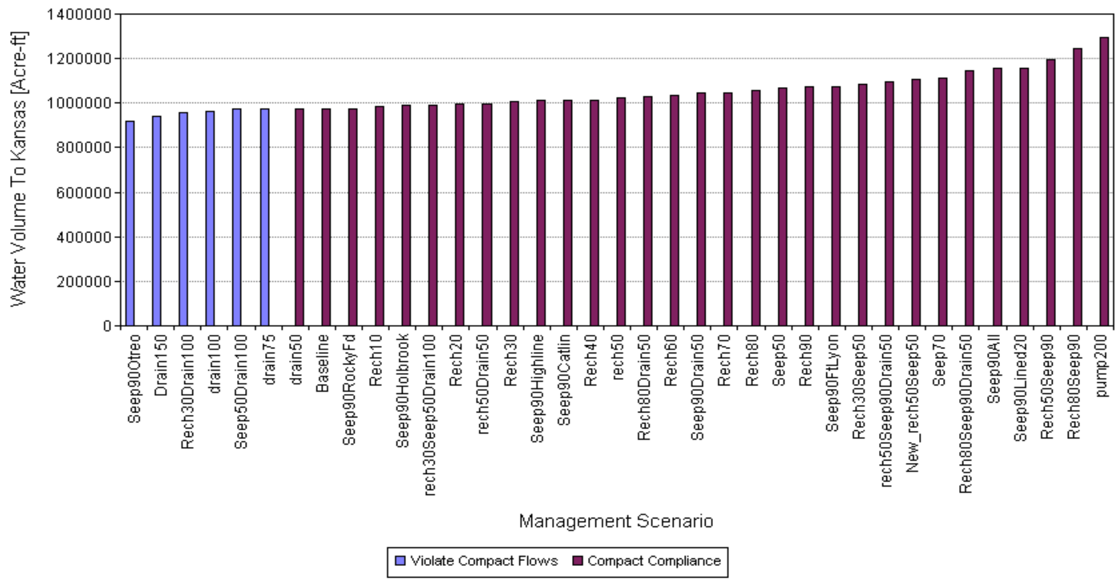

Figure 7.5 – Colorado-Kansas state line simulated flow in operational mode A for considered Management Alternatives

Stream-Aquifer Interaction for Operational Mode A

The basin-wide stream-aquifer interaction modeling performance is evaluated to provide an idea of the role in the comparative evaluation of alternatives. Basin-wide *LAR GeoDSS* predictions are presented to illustrate the behavior of the stream-aquifer interaction outside of the groundwater modeled area. The ANN-based predictions are analyzed for both the main stem and the tributaries.

Analysis in the Groundwater Modeled Area

In the groundwater MODFLOW-MT3DMS modeled area, the *LAR GeoDSS* prediction is compared against the MODFLOW-MT3DMS modeling. The regional-scale performance of the ANN predictions is analyzed using the net return flow averaged over the simulated period and over the six modeled grouping areas (i.e., 6, 7, 8, 9, 10, and 11) (Figure 4.2). Although smaller scale comparison is possible (e.g., by grouping area), it is believed that regional comparison is more descriptive of the performance in analyzing water management alternatives at the basin scale. Larger variability in the results is expected when comparing results per grouping areas, with ones results for some grouping areas better representing the MODFLOW-MT3DMS modeled values than others. Only a portion of grouping areas 6 and 11 are modeled in MODFLOW-MT3DMS; therefore, the volumetric result should consider the discrepancy inherited from the difference in the size of the modeled areas. The net return flow is computed for each time step in each grouping area as the Arkansas River accessions minus the depletions.

Return Flows Analysis

For the main stem, ANN-based net return flow and concentration prediction comparisons include all grouping areas modeled in MODFLOW-MT3DMS. Figure 7.6 shows weekly average net return flow comparison between MODFLOW-MT3DMS and the *LAR GeoDSS*, where the trend of return flow change is observed and a reduction in return flows is the most common result in both MODFLOW-MT3DMS and *LAR GeoDSS* simulation. In general, results show agreement in changes of return flow during simulation of the management alternatives with larger under predictions of return flows than over predictions, more often in management scenarios including drainage improvements. For each of the alternatives, Figure 7.7 shows the relative standard deviation or coefficient of variation (CV) over time and over grouping areas of the computed net return flow. The CV calculations reveal a larger spread of the results relative to the mean in the MODFLOW-MT3DMS predicted values than in the *LAR GeoDSS* predicted values.

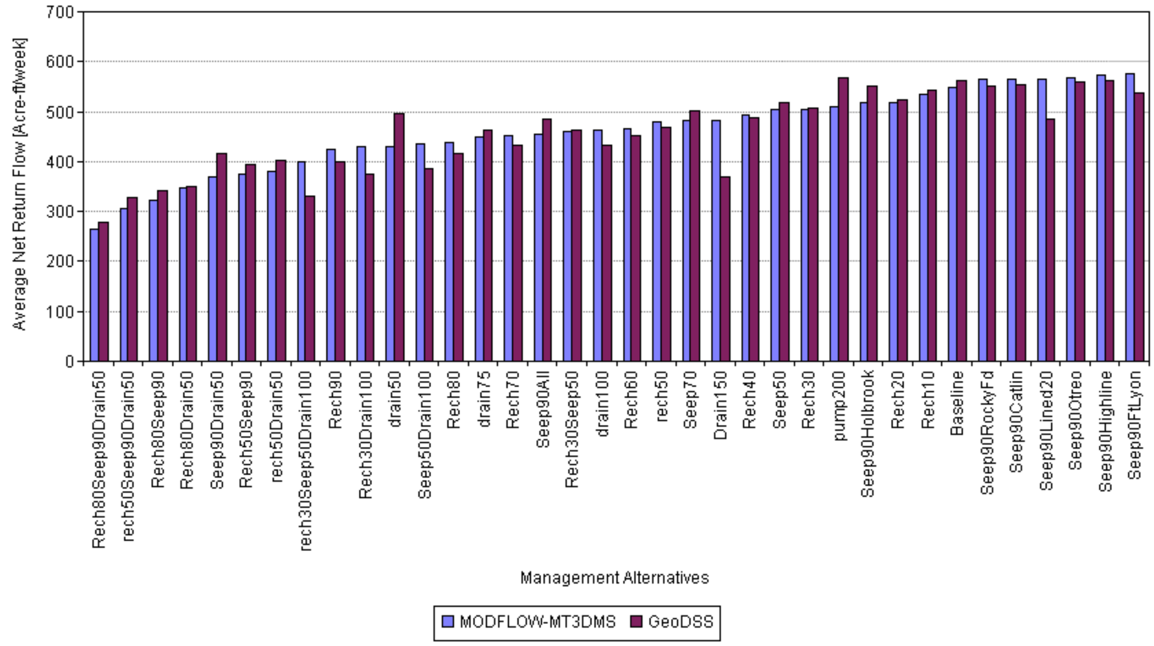

Figure 7.6 – Arkansas River average net return flow within the MODFLOW-MT3DMS modeled region for considered management alternatives

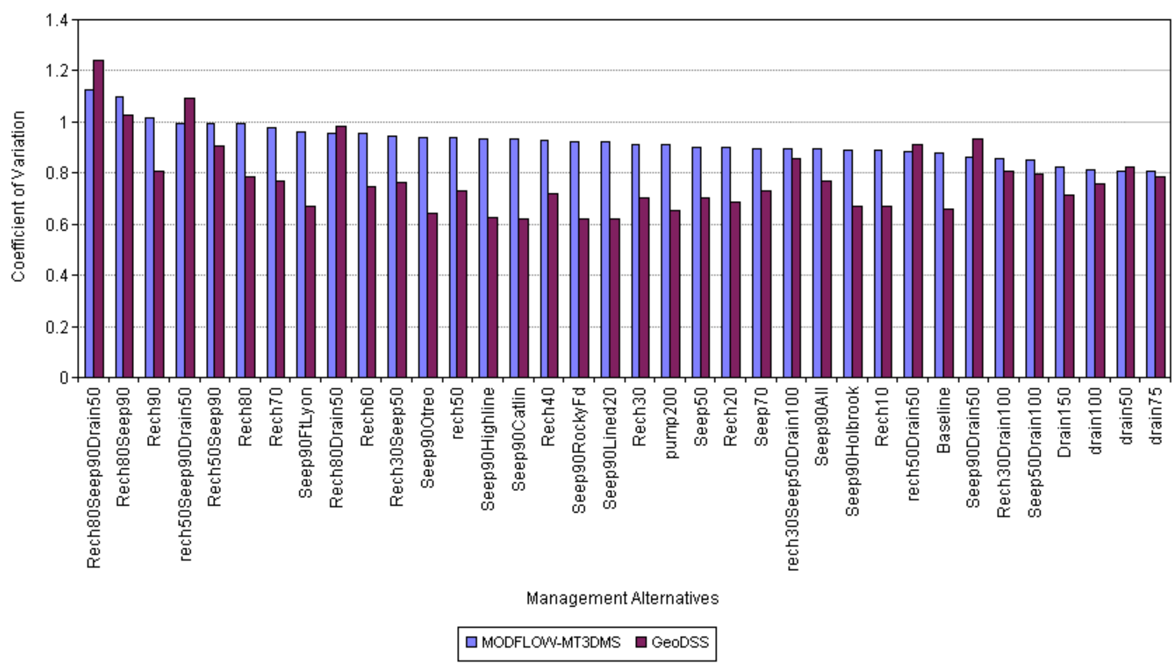

Figure 7.7 – Coefficient of variation of the Arkansas River net return flow within the MODFLOW-MT3DMS modeled region for considered management alternatives

The *LAR GeoDSS* average net return flow predictions for the tributaries in the MODFLOW-MT3DMS modeled region are compared in Figure 7.8. Contrary to the behavior observed in the Arkansas River return flow analysis, there is a clear tendency for larger over predictions of return flow in drainage improvement scenarios. It is likely that this is due to the smaller alterations to explanatory variables in the drainage improvements scenarios compared with other scenarios (only the drainage intensity explanatory variable is directly changed from the baseline). Further improvements to the ANN prediction of drainage improvement scenarios should consider the development of explanatory variables that can capture the effect of the return of additional drained water to the river system.

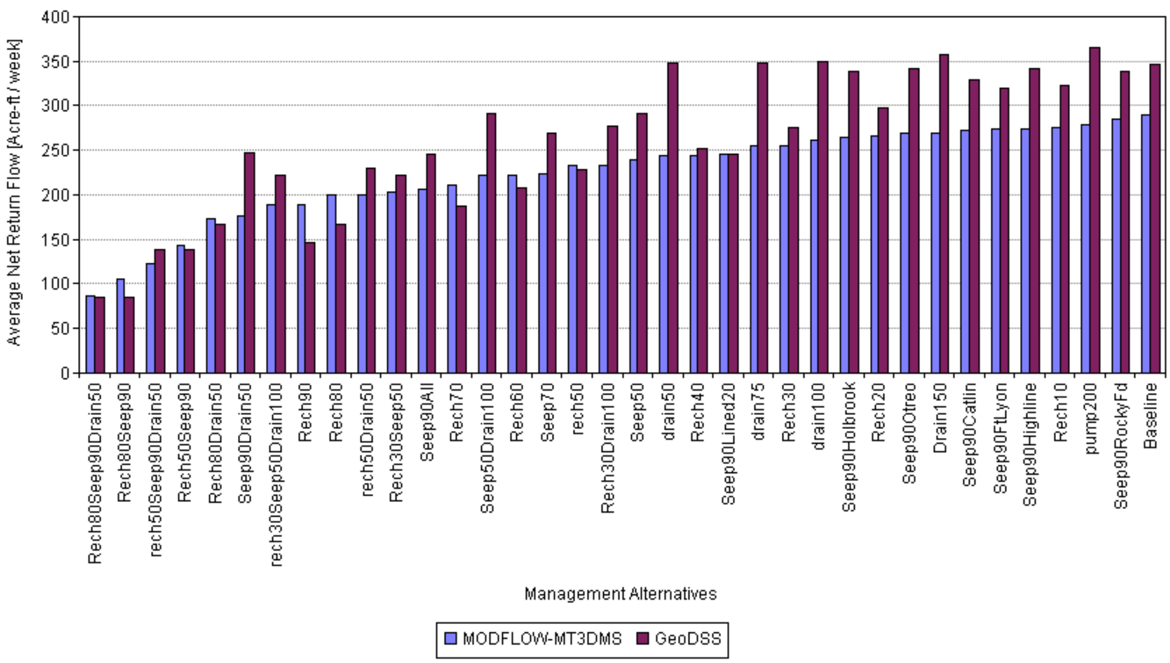

Figure 7.8 – Tributaries average net return flow within the MODFLOW-MT3DMS modeled region for considered management alternatives

The CV values for the tributaries return flow predictions are shown in Figure 7.9. Spread of both the MODFLOW-MT3DMS modeled and *LAR GeoDSS* predicted values for the tributaries are larger than the spread in the Arkansas River values. The increase of spread between the Arkansas River and tributaries return flows is well represented by the *LAR GeoDSS* predictions.

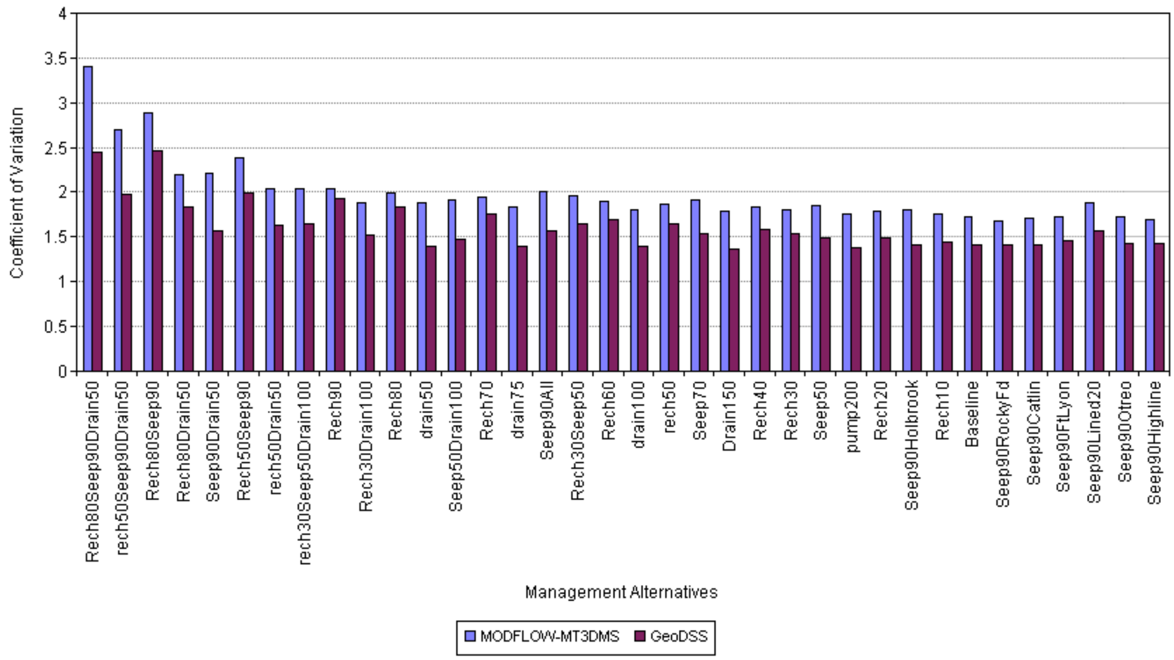

Figure 7.9 – Coefficient of variation of the tributaries net return flow within the MODFLOW-MT3DMS modeled region for considered management altenatives

The average error in the weekly return flow prediction is measured using the root mean squared error (RMSE). The RMSE for each of the management alternatives is shown in Figure 7.10. Even though average return flows to the tributaries are smaller than return flows to the Arkansas the RMSE of both predictions are in the same range, indicating a relatively larger error in the prediction of the tributary return flow. The maximum RMSE for the tributaries return flow prediction was found in the *Pump200* scenario. The RMSE for the Arkansas River return flow prediction is more uniform with relatively larger errors among alternatives with combined seepage, drainage and recharge alternatives; seepage improvements for individual canals; and drainage only alternatives.

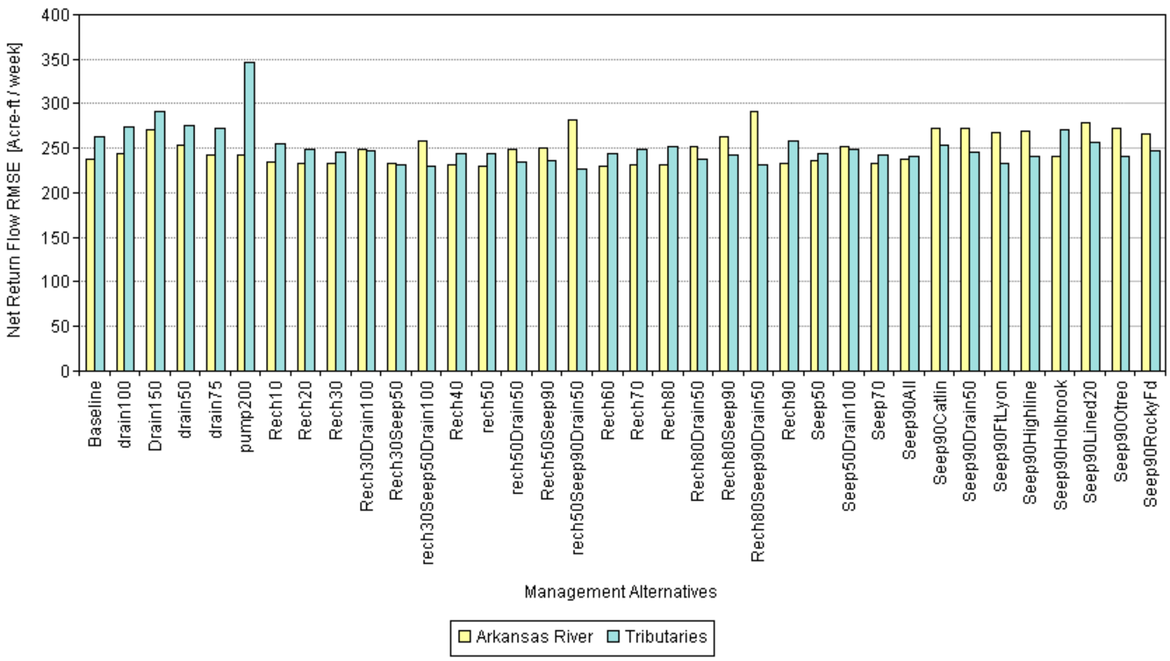

Figure 7.10 – RMSE of the net return flow prediction relative to the baseline for the Arkansas River within the MODFLOW-MT3DMS modeled region for considered management alternatives

Water Quality Analysis

Rather than analyzing the ANN-predicted return-flow concentration for the water management alternative simulations, it is more significant to analyze the salt load to the river from the groundwater, calculated as the product of the predicted return flow and concentration. This analysis allows observing changes in salt loadings to the surface system due to implementation of the water management alternatives. Figure 7.11 shows the average predicted weekly salt load to the Arkansas River. Results show under-prediction of the salt load for all the alternatives. Consistent under-prediction in salt concentration is the main reason for the under-estimation of salt loads. Special consideration should be given in interpreting these results because of the way the *LAR GeoDSS* output is generated. For cases where the ANN predicts a net depletion from a grouping area, the computed *LAR GeoDSS* salt load will be zero for this grouping area while it is computed at individual MODFLOW-MT3DMS return flow cells within the grouping area for the groundwater modeling summary. Although net depletions are not a common occurrence in this system, these cases of zero salt loading lower the computed *LAR GeoDSS* average salt load during the simulated period. The CV of the computed salt load to the Arkansas River in the groundwater modeled area is shown in Figure 7.12. Larger variability in the CV values is observable in *LAR GeoDSS* prediction. This is attributed to the combination of errors of individual predictions of flow and concentration that are used to calculate the salt load.

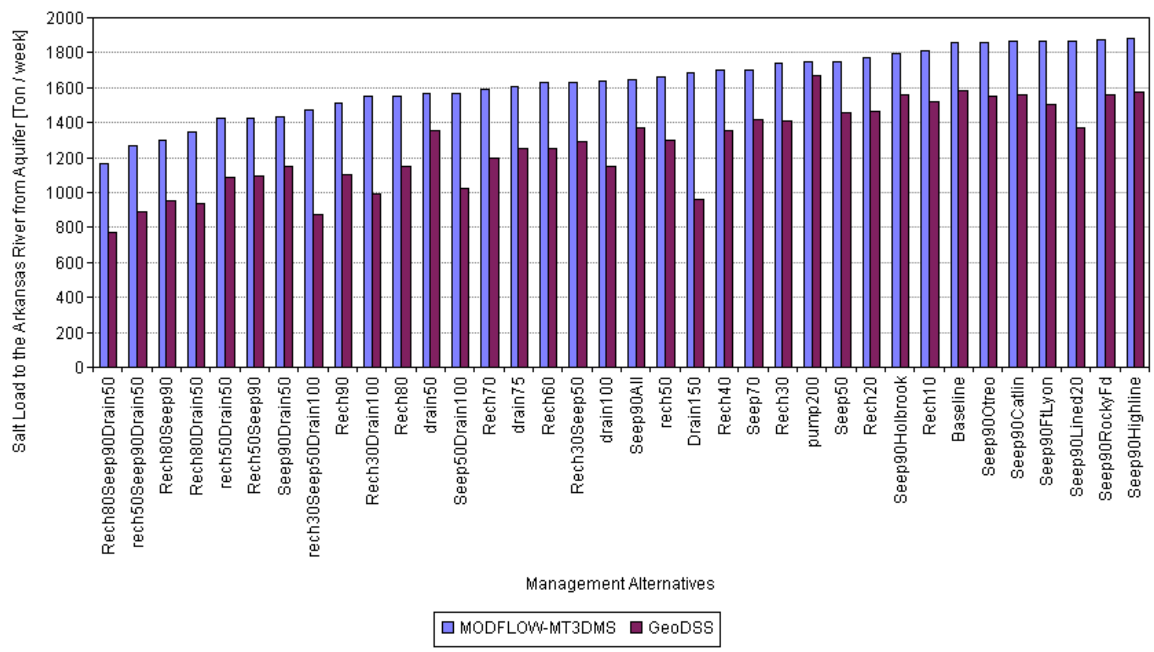

Figure 7.11 – Arkansas River average salt load within the MODFLOW-MT3DMS modeled region for considered management alternatives

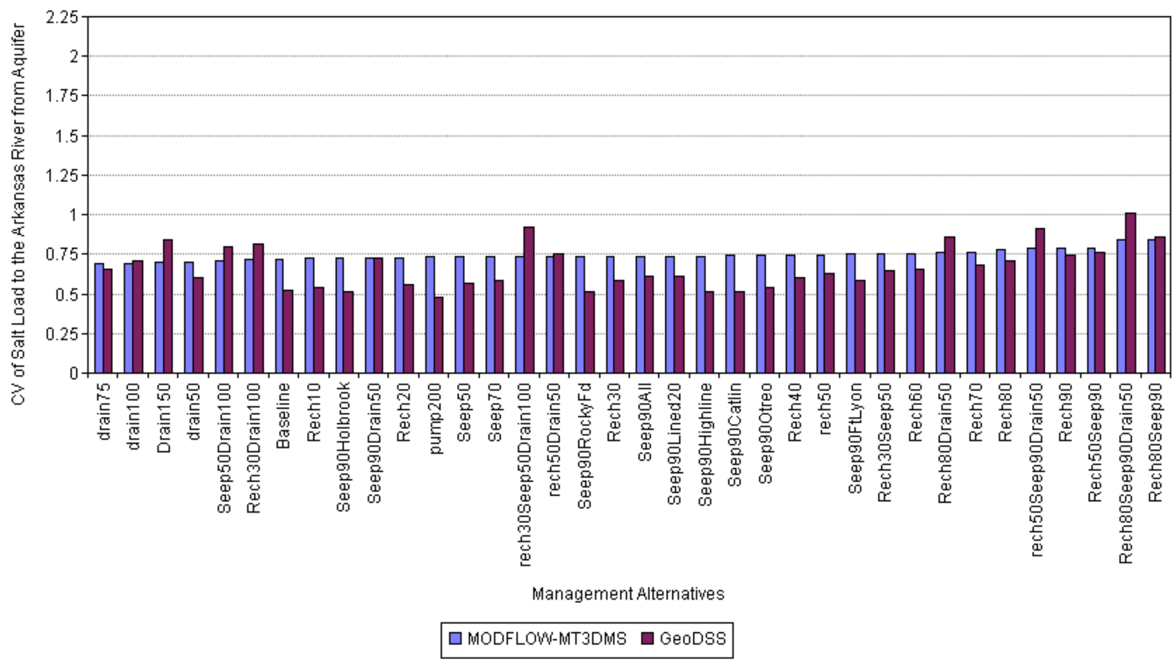

Figure 7.12 – Coefficient of variation of the Arkansas River salt load within the MODFLOW-MT3DMS modeled region for considered management alternatives

Salt load to the tributaries as the product of the predicted return flow rates and concentration is compared in Figure 7.13. Results show a total salt load to the tributaries smaller than the salt load returned to the Arkansas River. Over-prediction of the salt load is observed for management alternatives with only drainage improvements and only seepage improvements, and under-prediction occurs for alternatives with large reductions in areal recharge and canal seepage. The CV of the salt load to the tributaries is presented in Figure 7.14. In general, larger spreads are recognized in the tributaries salt load relative to the corresponding calculated values for the Arkansas River. The *LAR GeoDSS* predictions capture well the relative spreads with respect to the mean of the modeled values.

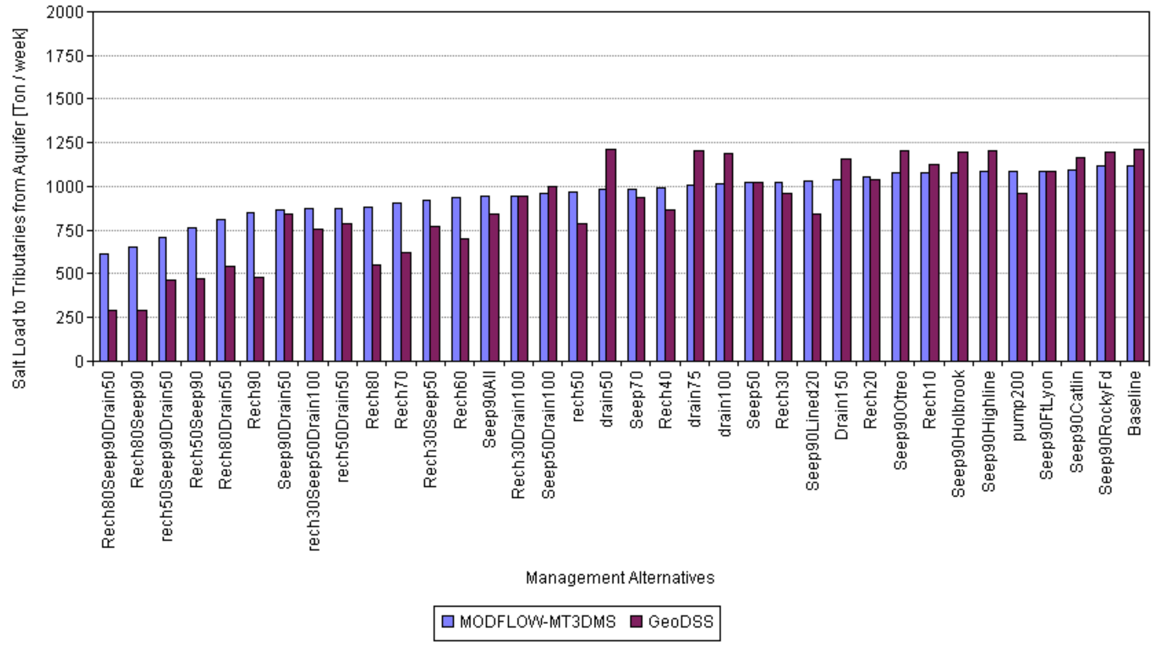

Figure 7.13 – Tributaries average salt load within the MODFLOW-MT3DMS modeled region for considered management alternatives

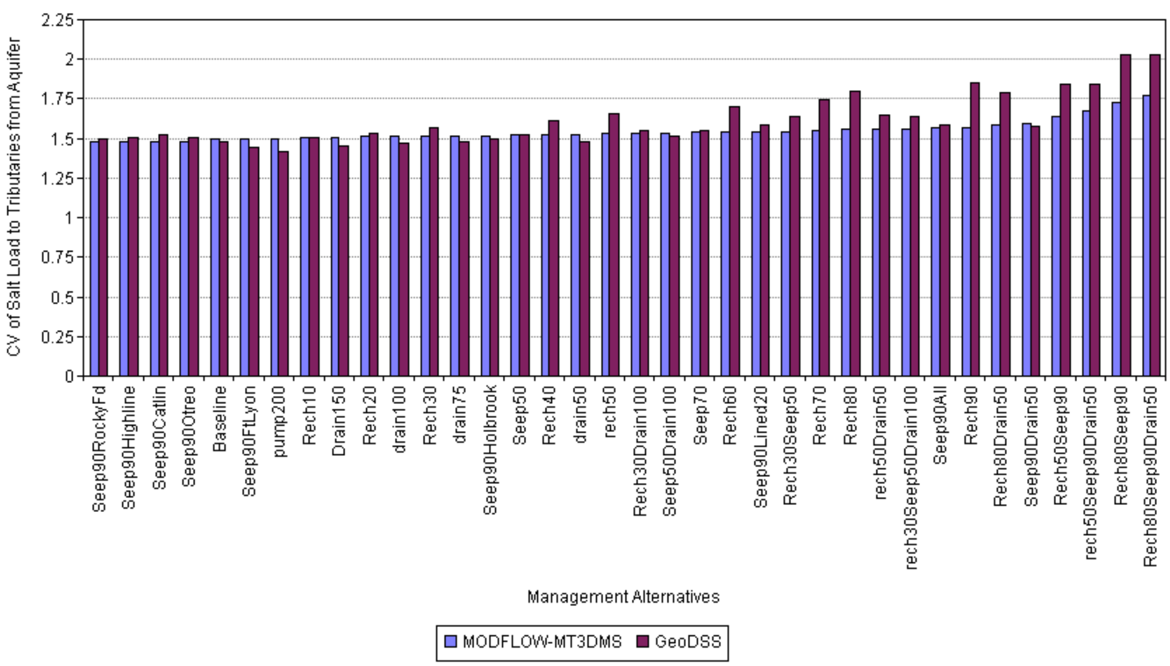

Figure 7.14 – Coefficient of variation of the Tributaries salt load within the MODFLOW-MT3DMS modeled region for considered management alternatives

The error in the prediction of average salt loads to the tributaries is summarized for each alternative using the RMSE (Figure 7.15). The magnitude and the variability of the prediction of salt loads are larger for the tributaries than for the Arkansas River. The wider relative spread identified for the tributary modeled concentration could influence the larger salt loadings errors. The MODFLOW-MT3DMS modeled tributary return flow concentrations have a higher variability than the modeled concentrations of the Arkansas River return flow, which could facilitate the ANN prediction of the concentrations for the main stem and consequently reduce the river salt load RMSE compared to the tributaries salt load RMSE.

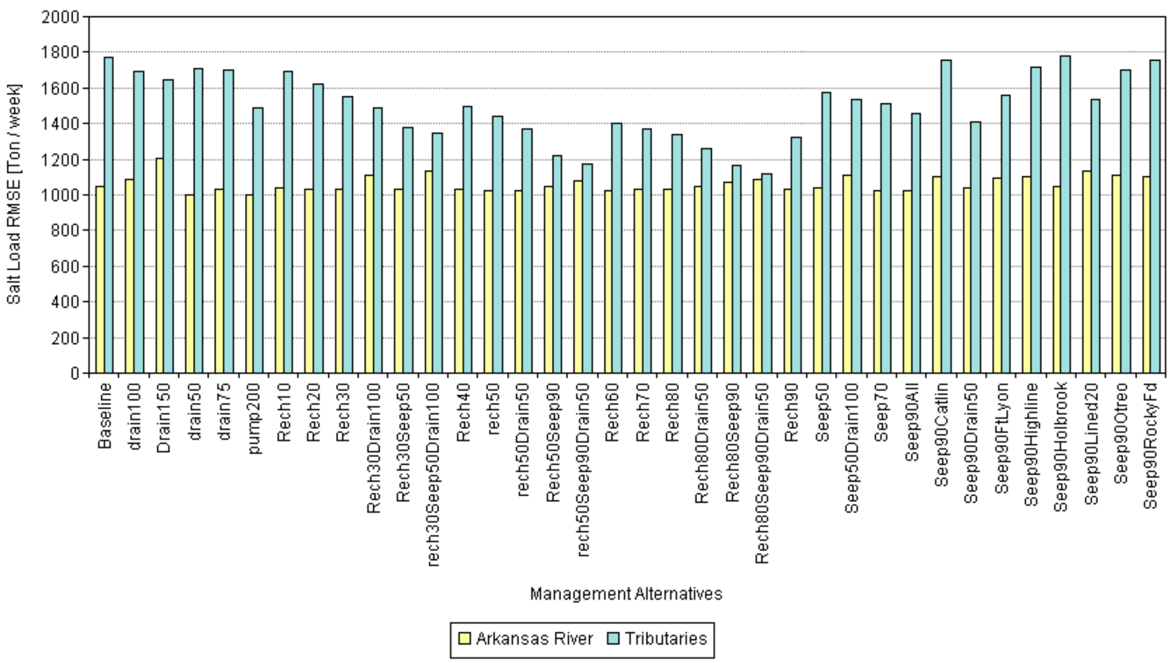

Figure 7.15 – RMSE of the salt load prediction for the Arkansas River and the tributaries within the MODFLOW-MT3DMS modeled region for considered management alternatives

Comparison of Predicted Changes Relative to the Baseline

Comparison of the change of predicted return flows relative to the baseline return flows reflects the relative ability of the ANN–based prediction to represent MODFLOW-MT3DMS simulated changes in stream-aquifer interaction for water management alternatives. Although comparing predictions relative to a predicted baseline value that itself has errors associated with it can be misleading, it is believed that this analysis provides a framework for the relative comparison and analysis of water management alternatives. Figure 7.16 shows the average change in net return flow from the baseline return flow for the Arkansas River in the MODFLOW-MT3DMS modeled area. *LAR GeoDSS* water management alternatives with larger predicted negative change than the corresponding MODFLOW-MT3DMS predicted change (e.g., Drain 150) indicate a larger return flow reduction predicted by the *LAR GeoDSS*. For all the considered alternatives, the MODFLOW-MT3DMS modeled change of return flows from the baseline averages -81.9 acre-ft/week (-101.0 x 10^3/week), ranging from -171.5 acre-ft/week (-211.5 x 10^3/week) to 816.6 acre-ft/week (1006.5 x 10^3/week). Figure 7.17 shows the comparison of the average changes from the baseline of return flows to the Arkansas River, with each point representing a management alternative average change in both MODFLOW-MT3DMS and the *LAR GeoDSS*. The points follow a linear trend with slope lower than 45°, indicating larger over-prediction of the change for larger MODFLOW-MT3DMS modeled changes. The coefficient of determination of the fitted line is 0.79. For all the water management alternatives, the RMSE of the change of return flow predicted by the *LAR GeoDSS* and the corresponding change modeled by MODFLOW-MT3DMS averages 109.3 acre-ft/week (134.4 x 10^3 m^3/week), ranging from 258.6 acre-ft/week (318.9 x 10^3 m^3/week) to 15.13 acre-ft/week (18.6 x 10^3 m^3/week).

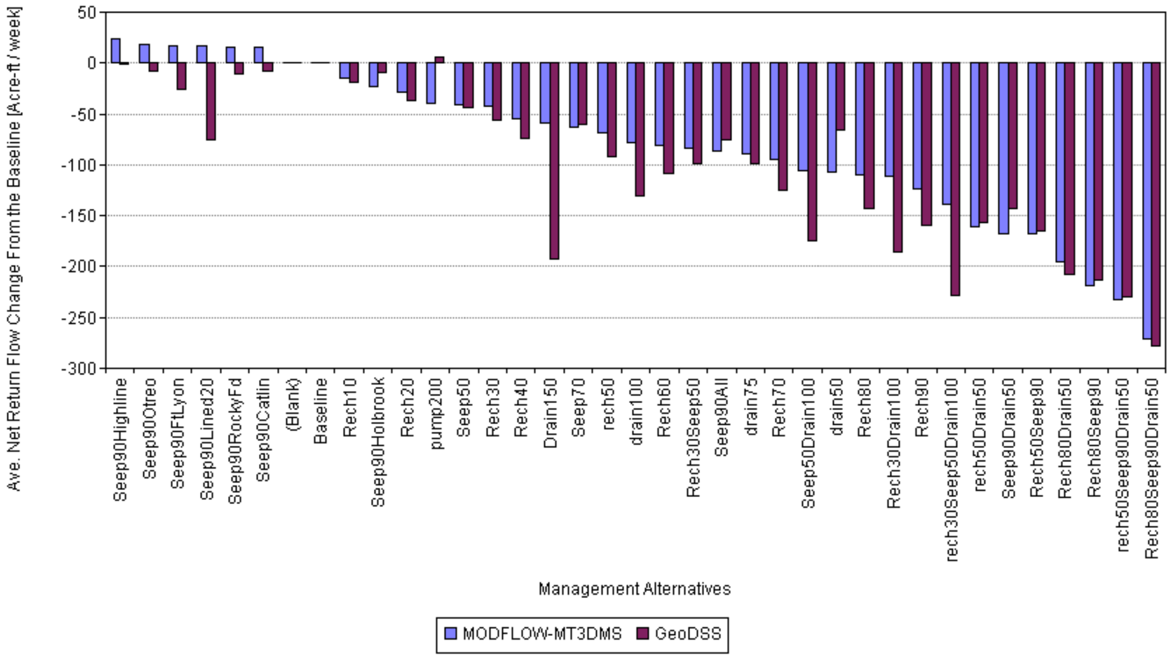

Figure 7.16 – Net return flow prediction change relative to the baseline for the Arkansas River within the MODFLOW-MT3DMS modeled region for considered management alternatives

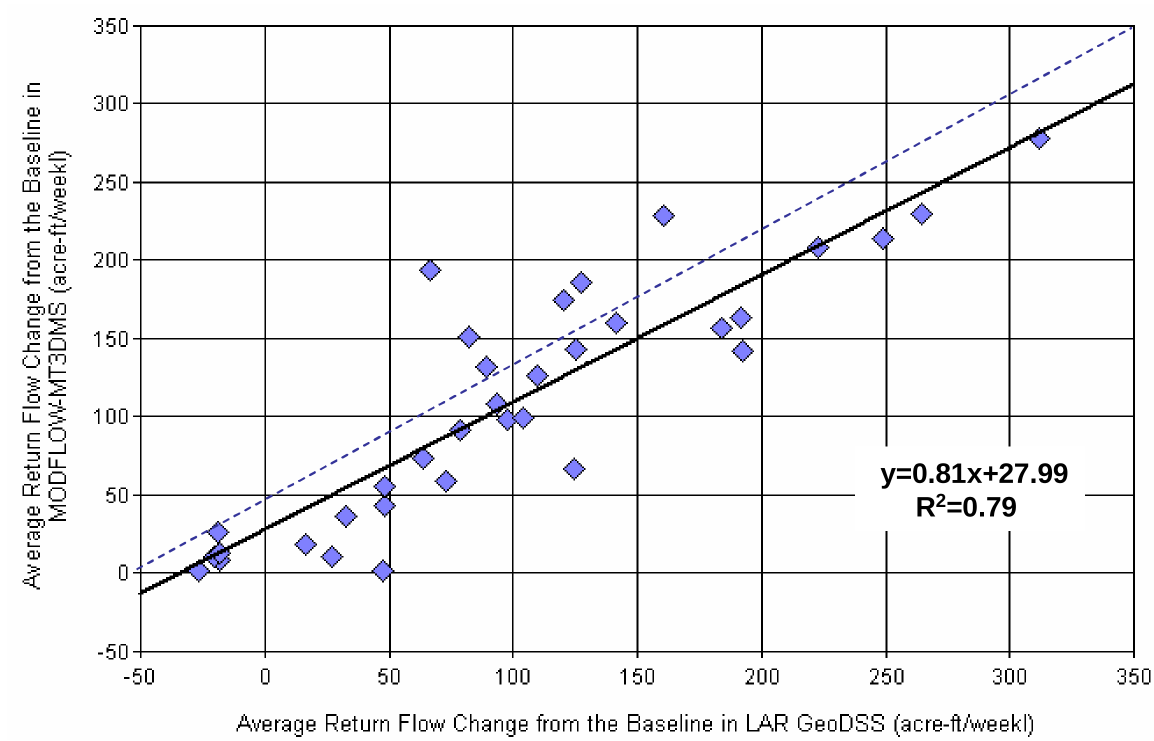

Figure 7.17 – Comparison of the average change from the baseline of return flow to the Arkansas River for considered management alternatives

The trend of the changes from the baseline suggests that a large fraction of the differences shown in Figure 7.16 can be attributed to localized larger errors rather than to generally biased predictions. Analysis of the CV of changes in return flow from the baseline is difficult to interpret due to the relatively small average change for some of the alternatives resulting in large CV values. The results show large CV values for both the *LAR GeoDSS*-predicted and the MODFLOW-MT3DMS modeled alternatives but not necessarily with the same magnitude and sign. Contrary to the findings regarding errors in the average return flow predictions, the larger CV differences (e.g., -12.5 for *Seep90Highline* scenario and 5 for *Seep90FortLyon* Scenario) could not be associated with a particular grouping area; therefore, discrepancies in relative spreads of predicted and modeled change from the baseline is found across all alternatives and grouping areas.

MODFLOW-MT3DMS modeled alternatives showing small positive change, indicating an increase of the return flow relative to the baseline, correspond to alternatives with localized improvements. Although the ANN explanatory variables can capture changes in the system stresses due to the improvements, it is believed that the differences observed in the results are a consequence of localized effects in the groundwater model that cannot be captured well in the generalized ANN prediction. The same reasoning of localized effect could apply for the single pumping scenario.

Figure 7.18 shows the average change of return flow predictions from the baseline for both the *LAR GeoDSS* and MODFLOW-MT3DMS modeled values in the tributaries. In this case, there is a consistently larger reduction of return flow in the areal recharge reduction scenarios modeled by the *LAR GeoDSS*, and a consistently smaller reduction of return flows in the drainage improvement scenarios. These comparative differences in predictions can result from the difficulty in predicting highly localized tributary return flow changes using explanatory variables that are defined for grouping areas that capture regional changes in system stresses. For all the considered alternatives, the MODFLOW-MT3DMS modeled change of return flows to the tributaries from the baseline averages -66.2 acre-ft/week (-81.65 x 10^3 m^3/week), ranging from 202.5 acre-ft/week (249.7 x 10^3 m^3/week) to 4.0 acre-ft/week (4.9 x 10^3 m^3/week). The average RMSE of change of return flow from the baseline predicted by the *LAR GeoDSS* and MODFLOW-MT3DMS is 60.0 acre-ft/week (74.0 x 10^3 m^3/week), ranging from 132.0 acre-ft/week (162.8 x 10^3 m^3/week) to 8.0 acre-ft/week (9.8 x 10^3 m^3/week)

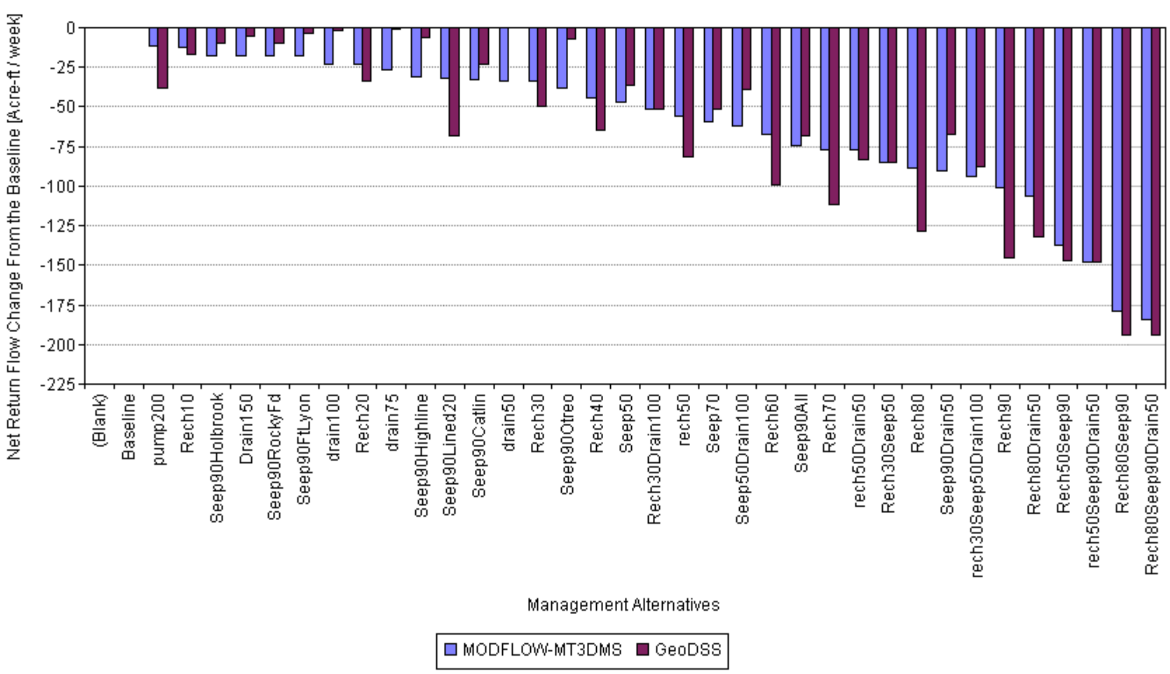

Figure 7.18 – Net return flow prediction change relative to the baseline for the tributaries within the MODFLOW-MT3DMS modeled region for considered management alternatives

The comparison of the average changes for each of the alternatives between the MODFLOW-MT3DMS modeled and the LAR GeoDSS is shown in Figure 7.19. The points representing each alternative are fitted to a linear function indicating a trend that under-predicts changes for larger MODFLOW-MT3DMS changes and represents fairly well small changes, except for the localized improvement alternatives with average negative changes modeled in MODFLOW-MT3DMS.

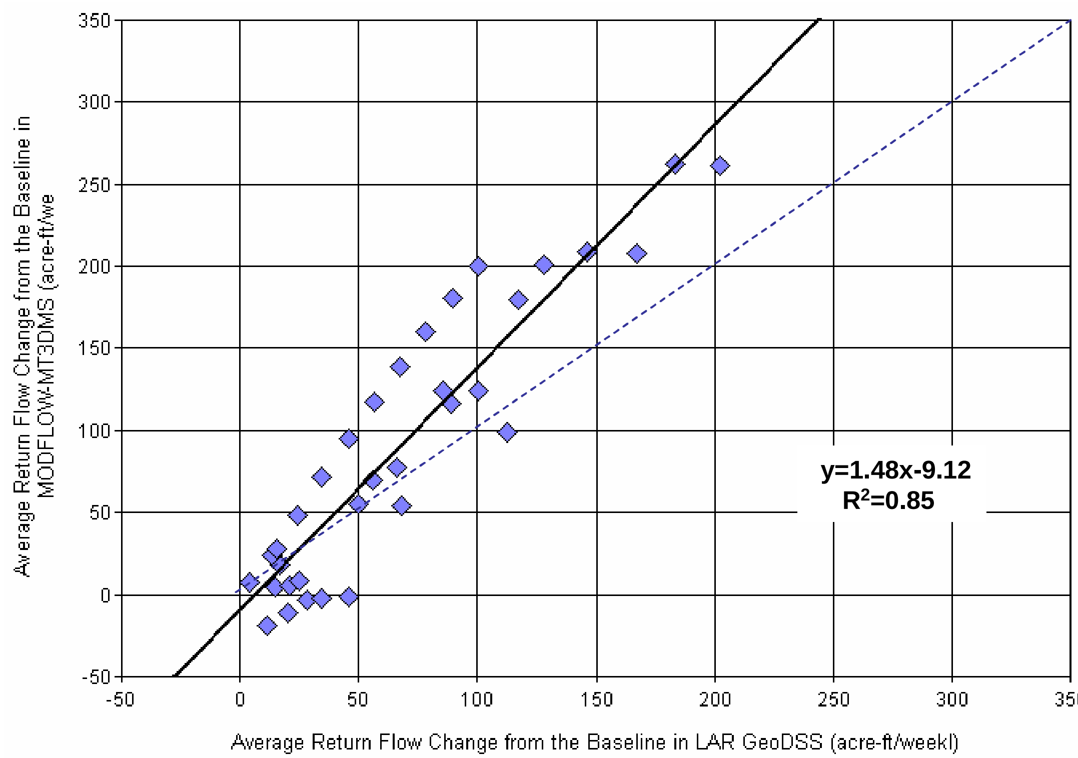

Figure 7.19 – Comparison of the change from the baseline of return flow to the tributaries for the considered management alternatives

Salt load change from the baseline is compared between the *LAR GeoDSS* prediction and the MODFLOW-M3TDMS modeled values in Figure 7.20 for the Arkansas and Figure 7.21 for the tributaries. These results are the product of the flow and concentration predictions, therefore exhibiting both prediction errors. Results are presented excluding grouping area 11 which was shown in the flow analysis to contribute large discrepancies due to the modeled features outside the MODFLOW-MT3DMS modeled area.

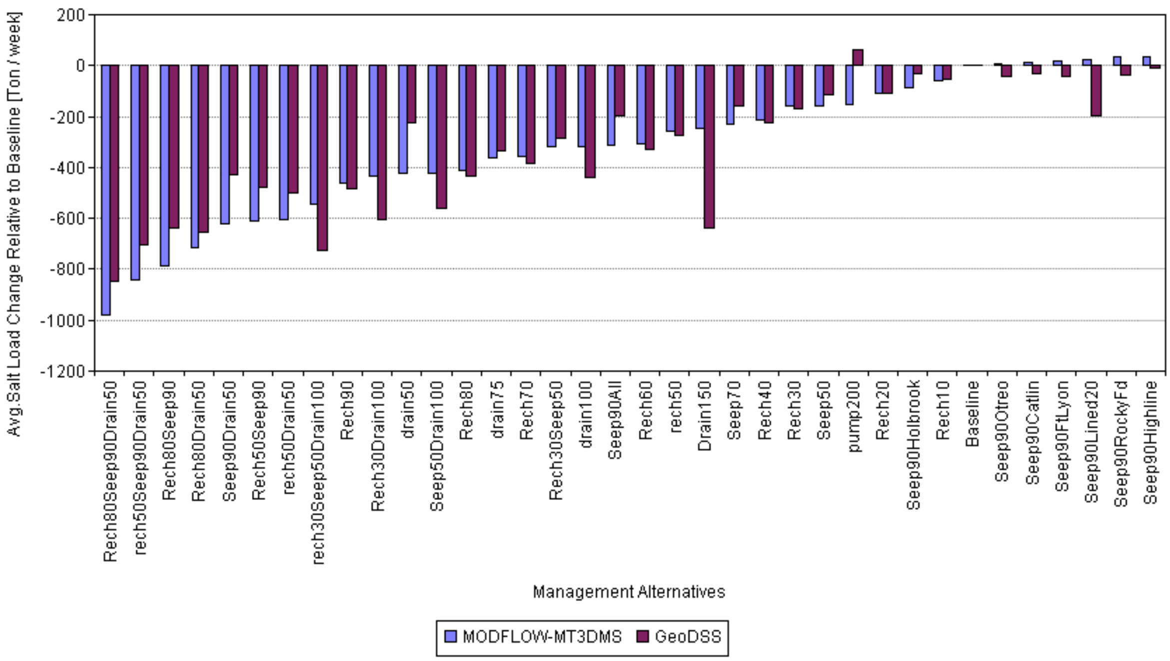

Figure 7.20 – Computed salt load prediction change relative to the baseline for the Arkansas River within the MODFLOW-MT3DMS modeled region for considered management alternatives

The largest discrepancies in Figure 7.20, where change in the *LAR GeoDSS* prediction is larger than change in the MODFLOW-MT3DMS prediction, imply under-prediction of salt loads to the Arkansas River. These discrepancies are mainly caused by a consistent under-prediction of return flows in grouping area 10 combined with a larger reduction of salt concentration than that modeled by MODFLOW-MT3DMS. The system stress changes modeled in the water management alternatives are harder to be fully captured by explanatory variables within small areas, especially when few irrigated fields and canal diversions intersect the grouping area (e.g., grouping area 10); therefore, changes relative to the baseline in these areas are expected to have less capability to adequately represent the MODFLOW-MT3DMS modeled changes.

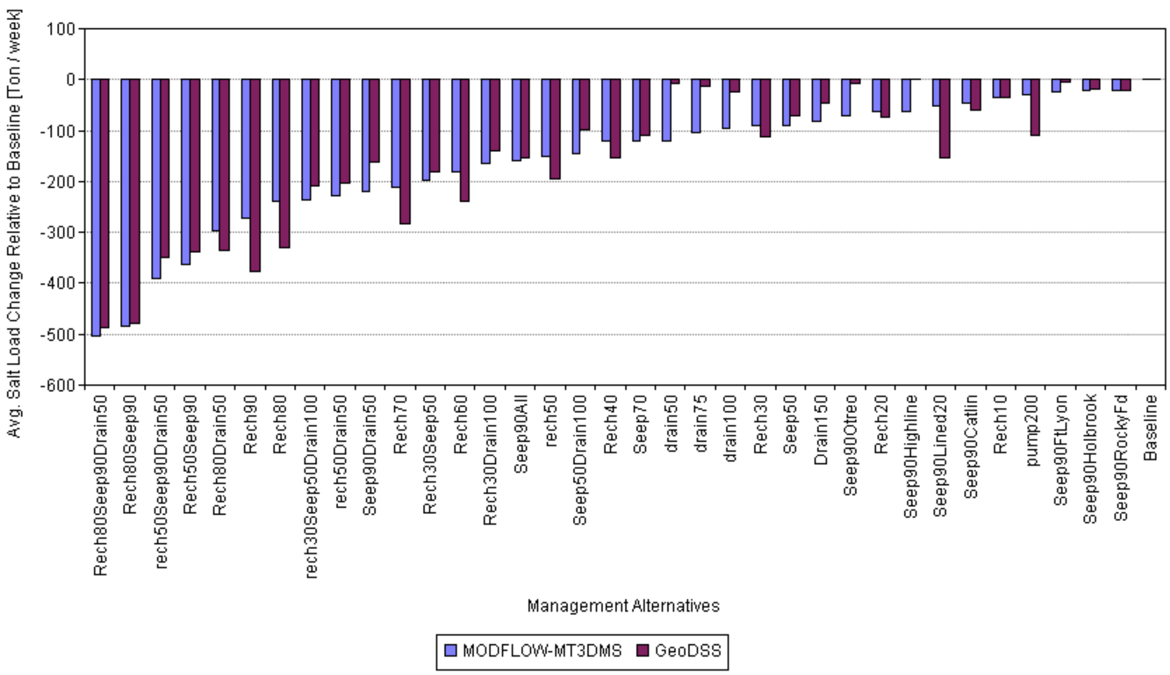

Figure 7.21 – Computed salt load prediction change relative to the baseline for the tributaries within the MODFLOW-MT3DMS modeled region for considered management alternatives

A large portion of the discrepancies in Figure 7.21 between the *LAR GeoDSS* computed and MODFLOW-MT3DMS modeled salt load change occur due to results from grouping area 6. Besides this grouping area being partially modeled in MODFLOW-MT3DMS, it includes a MODFLOW-MT3DMS modeled tributary that crosses into groping area 7 where it converges with the Arkansas River. Although the length of this tributary line within the network is 6.5 km, the MODFLOW-MT3DMS modeled length of the tributary inside grouping area 7 is less than 1 km; therefore, the tributary is not modeled in *LAR GeoDSS*. Not modeling this tributary neglects the return flows inside area 6, contributing an underestimation of return flow in this area.

Description of Sources of Uncertainty in the Stream-Aquifer Interaction Modeling

Although direct coupling of MODFLOW-MT3DMS and Geo-MODSIM could provide stream-aquifer interaction modeling in *LAR GeoDSS*, the ANN-based methodology to model stream-aquifer interaction in *LAR GeoDSS* allows the simulation of conjunctive use of surface and ground water quantity and quality basin-wide utilizing results from only a partial coverage of the basin for which detailed data and MODFLOW-MT3DMS model results were available. Discrepancies presented in the previous sections are in large part a result of the uncertainty in the implemented methodology.

The basin-wide simulation of return flows and salt concentrations require introducing procedures that increase the uncertainty in the predictions observed during the ANN training and testing stage. The ANN priming procedure estimates a likely starting condition based on calculated explanatory variables for the initial time steps but it could introduce a false start error that will propagate over the entire simulation period. The modeled process memory in the ANN explanatory variables, represented by the inclusion of previous time step conditions of the system, is another source of uncertainty. Basin-wide predictions require the use of previously predicted values (i.e., return flows and corresponding concentrations) as explanatory variables, resulting in a propagation of errors that is magnified by the false start error. Simulations for this case study start in a historically wet period (i.e., April 1999) increasing the usual instabilities and oscillations associated with transient finite difference model initial time steps. Although the MODFLOW-MT3DMS results for the very first time steps are excluded from the ANN training, the ANN-based simulation still requires predictions over the initial time steps to guide future predictions. Off-track predictions for the initial time steps could be a cause for the entire simulation predictions to stay off-track, as mentioned in the salt loadings analysis where some of the concentration predictions are uniform under prediction of the change from the baseline.

Basin Scale Predictions

The basin-wide ANN-based predictions of average net return flow to the Arkansas River and tributaries are shown in Figure 7.22. Although stress magnitude and change characteristics may be different when analyzed at the basin scale relative to the regional MODFLOW-MT3DMS modeled area, the results show predictions in the range of those obtained for the modeled area (see Figures 7.6 and 7.8). Basin-wide predictions of changes (generally reductions) in net return flow from the baseline are similar to those analyzed in the previous sections for the *LAR GeoDSS* predictions within the MODFLOW-MT3DMS modeled area.

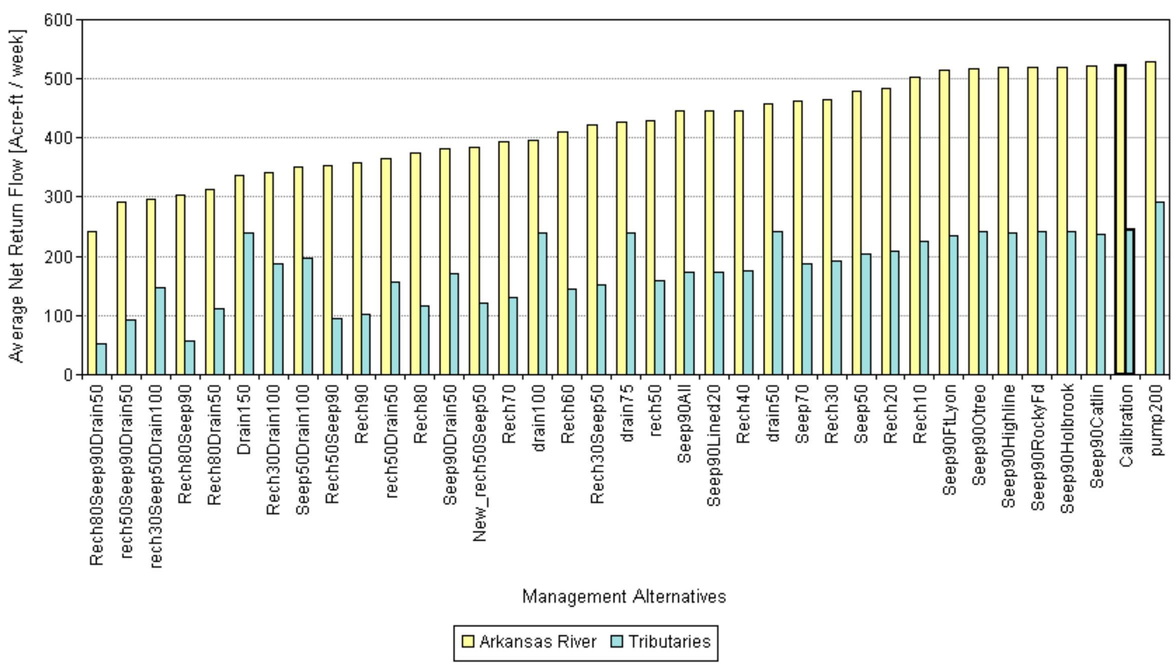

Figure 7.22 – Basin-wide average predicted net return flow per consider water management alternative

The spread of the basin-wide predictions is analyzed computing the CV over all grouping areas and time periods for each water management alternative. Figure 7.23 shows the CV for both the Arkansas River and tributaries net return flow predicted by *LAR GeoDSS*. Over all the simulated water management alternatives, the relative spread of tributary net return flow predictions at the basin scale tend to be larger than the corresponding CVs computed within the MODFLOW-MT3DMS modeled area; contrarily, the Arkansas River net return flow prediction spread are in general reduced in the basin-wide prediction compared to the regional predicted CVs. Changes in the tributary prediction CVs at the basin scale are attributed to the dissimilarity of tributary features modeled in the grouping areas across the basin since length and density of modeled tributaries can change markedly from one grouping area to another. On the other hand, Arkansas River net return flow is predicted for similar lengths of stream in all grouping areas favoring predictions that maintain the relative spread, as observed. Further conglomeration of predictions around the mean can be attributed to less variability of the computed explanatory variables compared with the corresponding values within the MODFLOW-MT3DMS modeled area.

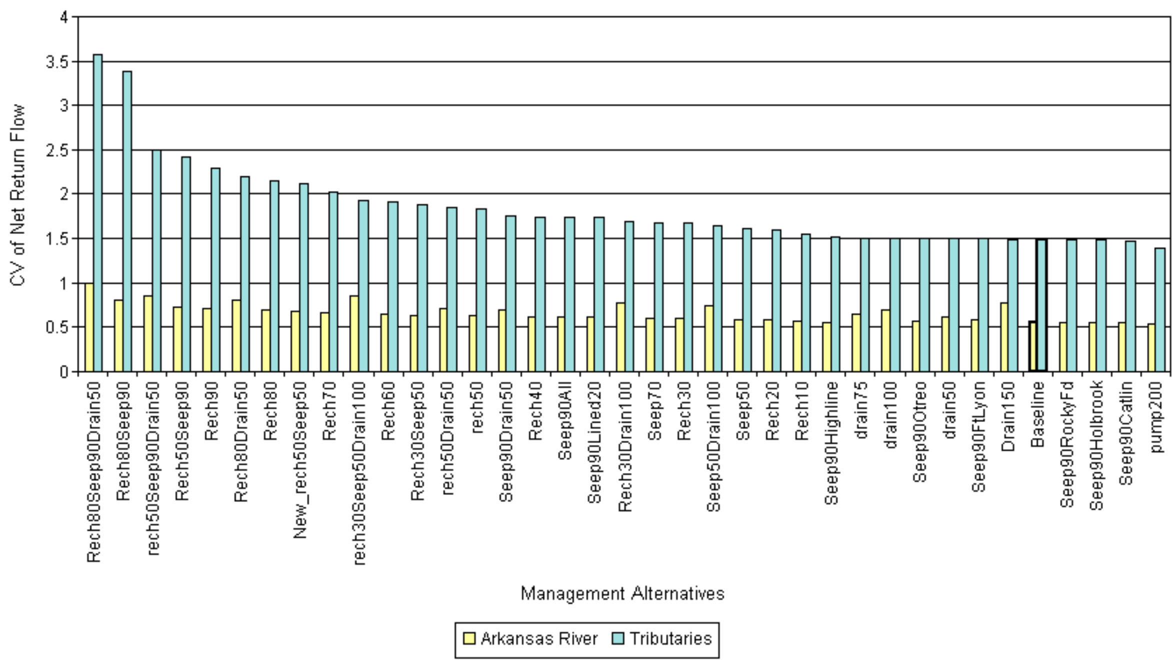

Figure 7.23 – Coefficient of variation of the basin-wide *LAR GeoDSS* predicted net return flow for considered management alternatives

Basin-wide predicted salt loadings and their relative change among the simulated water management alternatives are shown in Figure 7.24. Based on the observed average MODFLOW-MT3DMS modeled values of salt loadings, the *LAR GeoDSS* predicts basin-wide salt loadings that are reasonable, likely having the same under-prediction tendency identified in the previous analysis for predictions inside the MODFLOW-MT3DMS modeled area. No appreciable differences are found between the CVs of the *LAR GeoDSS* predicted salt loadings computed basin-wide and those within the MODFLOW-MT3DMS modeled area, as presented in Figures 7.12 and 7.14.

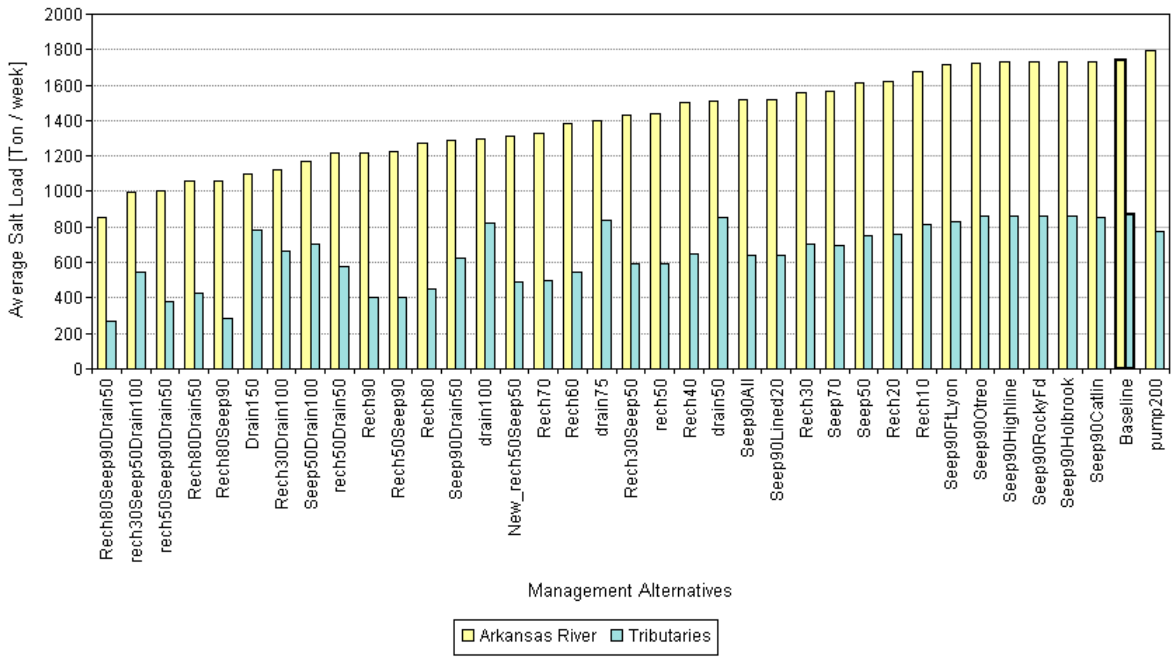

Figure 7.24 – Basin-wide salt loading to the Arkansas River and tributaries predicted by the *LAR GeoDSS* for considered management alternatives

River Water Quality for Operational Mode A

The predicted river basin soil and water quality is improved through the implementation of the management alternatives. Dilution takes place while running the non-diverted river water through the system, replacing more-concentrated return flows with less-concentrated non-diverted water. For the water management alternatives simulated, improvements in water quality throughout the system were evaluated using the average simulated TDS concentrations at key points in the river. The average simulated concentration at the system diversion points indicate improvement in the water applied to the fields with a consequential increase in crop yield and better water quality for municipal and industrial use, reducing water treatment costs. Figure 7.25 presents a summary of the average concentrations of the basin-wide diverted water for the simulated alternatives. Results show an overall reduction in concentration at the diversion points relative to the historical concentrations. This concentration reduction is caused by a dilution effect of water that is not diverted during the management alternatives simulation, replacing more concentrated return flows. Management alternatives with insignificant change in the diverted water concentration correspond to the alternatives with localized area of influence, such as the single canal seepage improvement alternatives. The results show that the best average diverted water concentrations are achieved with the combined alternatives, the best being *Rech80Seep90Drain50*.

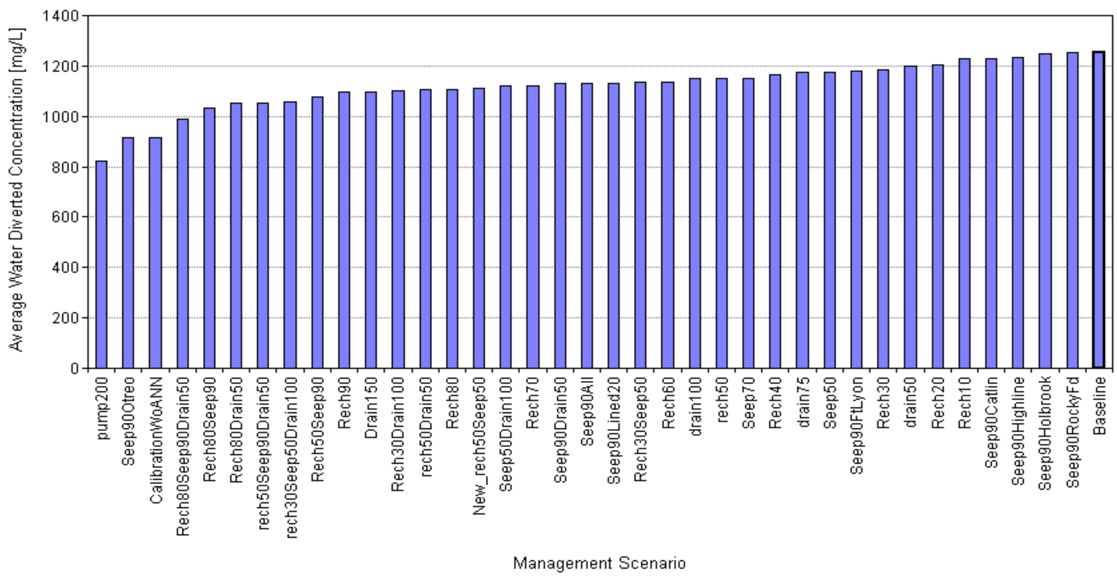

Figure 7.25 – Average diverted water concentration per management alternative in operational mode A

Management alternatives that lower the average concentration of the diverted water improve the quality of the soil by reducing the salt loading to the soil during irrigation, and also imply lower treatment costs for municipal use, resulting in a net basin-wide benefit. The reduction in concentration of diverted water also demonstrates the basin-wide benefit of replacing saline return flows with less concentrated non-diverted water. In addition, the previous results imply that, in most of the alternatives, water transported in the surface system has a lower concentration than that under baseline conditions. Therefore, it could be inferred that water depleted from the stream and canals will have a lower concentration than the modeled water in the baseline, thereby contributing to further improvement in the aquifer water quality.

The predicted salt concentration of flows delivered to Kansas demonstrates that the management alternatives not only provide the volume of water that meets the Arkansas River Compact, but also cause improvement in the water quality. Figure 7.26 summarizes the average concentration of the simulated flows provided to Kansas, with larger reductions corresponding to alternatives with basin-wide influence and more intensive intervention and smaller or insignificant reductions corresponding to alternative with small area of influence or moderate to low levels of improvement. Implementation of the management alternatives produces changes in total salt load at the Colorado-Kansas state line. Figure 7.27 shows the average salt load per week in flows at the Colorado-Kansas state line. Most of the alternatives result in reductions in salt loadings; however, alternatives with the largest increase in water volume to Kansas relative to the baseline result in an increase of salt loadings.

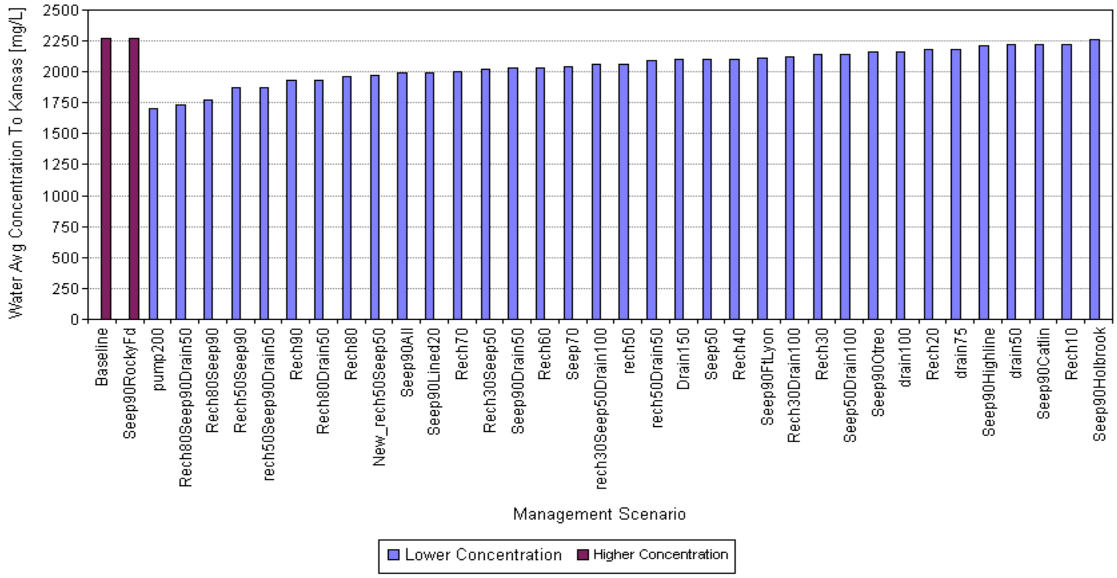

Figure 7.26 – Average water concentration provided to Kansas for considered management alternatives

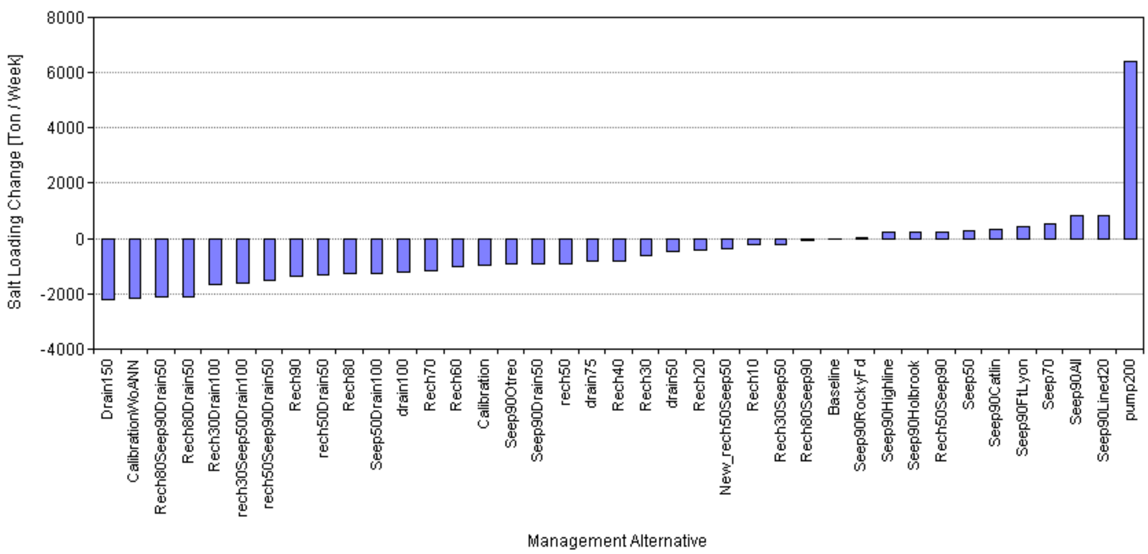

Figure 7.27 – Salt loading change at the Colorado-Kansas state border for considered management alternatives

John Martin Reservoir Salt Transport for Operational Mode A

Water quality entering John Martin Reservoir was analyzed to observe potential improvements in water released from the reservoir. Figure 7.28 shows a summary of the total salt entering from the Arkansas and Purgatoire Rivers and leaving the reservoir during the simulated period per management alternative. Salt load entering the reservoir is used to sort the alternatives display. Results show a reduction of salt load entering and leaving in almost all of the alternative simulations compared to the baseline, indicating an overall lower salt transport through out the system.

The averages of the water quality transport coefficient (Equation 7.24) for the management alternatives are presented in Figure 7.29. The coefficient T_r is greater than one (averaging $\overline{T}_r = 1.37$) for all alternatives, corroborating the assertion that in all cases the salt load released from the reservoir is greater than the load entering the reservoir. The ANN-based simulation in many alternatives resulted in an increase in the transport coefficient, thereby indicating a net larger salt load released per unit load entering the reservoir. The increase in salt loads released from the reservoir is most likely associated with the larger flows being released in this operational mode. As a cursory check, assuming that at least the baseline reservoir release flows are duplicated in the releases occurring under each alternatives, the lower salt loads leaving the reservoir most likely imply a lower concentration downstream.

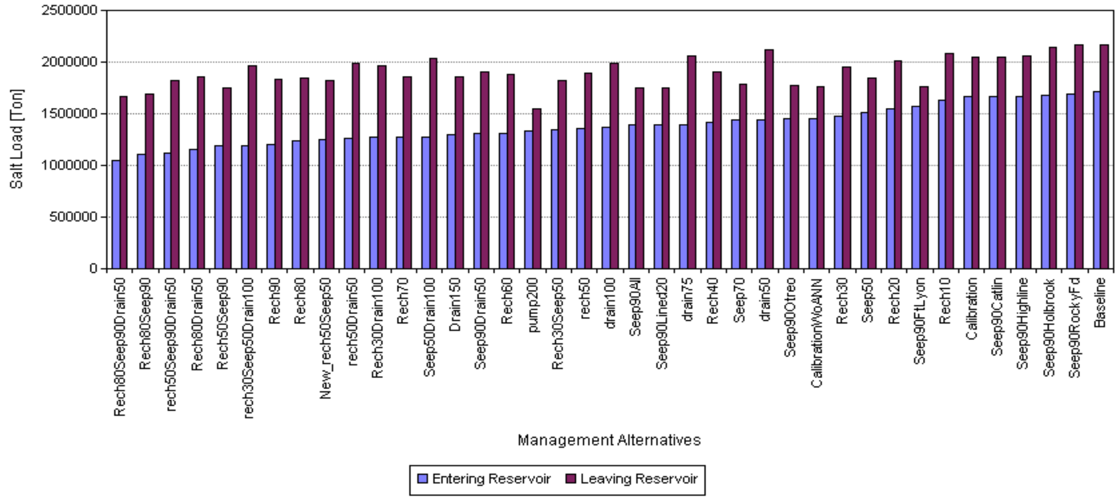

Figure 7.28 – Salt balance in John Martin Reservoir for operational mode A for considered management alternatives

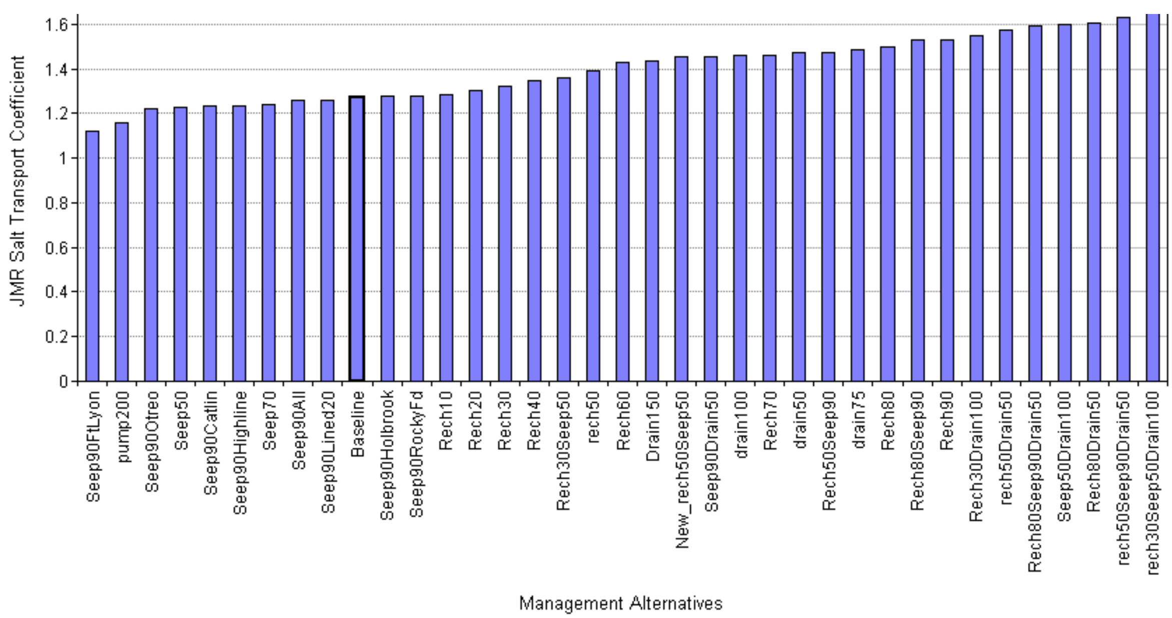

Figure 7.29 – John Martin Reservoir water quality transport coefficient in operational mode A for considered management alternatives

<u>Remarks on Results under Operational Mode A</u>

Although, in this mode the reservoirs did not store additional water and release it to match baseline return flows, the mode assumes that (1) all users in the basin participate in the program (i.e., less water is diverted) and (2) the non-diverted water runs downstream along the river within the same time step. Therefore, the occurrence of relatively small or no shortages indicates that the dynamics of the system would allow implementation of several management alternatives with minimum changes to the operating polices. In the case that the water allowed non-diverted flows could be earmarked for agricultural activities, this water could be added to the natural flow and increase available flows to downstream users in the basin. In this situation, junior diversions that historically diverted less water than their actual water demand could divert more to meet water demands, without implying non-participation in the program and without bringing more agricultural land into production. It is important to point out that the simulated period was historically a transition from wet to dry conditions. The stream-aquifer system modeled is probably in transition to a new dynamic equilibrium that is going to affect the storage water requirements, requiring more water from storage if return flows are reduced once the new dynamic equilibrium is reached. Extending the simulation period will reveal the storage requirement for this dynamic equilibrium condition.

The analysis of the stream-aquifer interaction modeling in the *LAR GeoDSS* reveals reasonable agreement in the percentage of the volume change from the baseline net return flows. Comparisons between the regional MODFLOW-MT3DMS-modeled results and the basin-wide *LAR GeoDSS* results show a reasonably similar tendency (i.e., direction of change) in the overall predictions. Average salt concentrations of aquifer return flows in MODFLOW-MT3DMS for the simulated alternatives showed small disagreement with respect to the baseline concentrations. Changes in average return flow concentrations modeled by MODFLOW-MT3DMS relative to the baseline for all the management alternatives ranges from -32 mg/L and +96 mg/L, which in most of the cases is expected to be smaller than the average ANN predicted concentration error due to the ANN imperfect explanatory variables and the ANN priming procedure. Therefore, it is believed that return flow concentrations for alternatives simulated in the *LAR GeoDSS* with average predicted concentrations that fail to agree with the direction of the change modeled in MODFLOW-MT3DMS have little impact on interpretation of the results.

Table 7.3 shows a summary of the performance of the considered management alternatives for the primary evaluation criteria. Total water shortages greater than 100 acre-ft (123,348.2 m^3) during the simulated period are considered infeasible and labeled as *large*, while small shortages are defined as those greater than zero and less than or equal to 100 acre-ft. The system end-of-storage is compared with the historical volume, considering *lower* conditions to be those where water is left in the reservoirs but is lower than the historical volume. The reservoir system condition *empty* occurs when there is no water left after the simulation and is considered as infeasible. Simulations that are unable to match historical flows at the Colorado-Kansas state line are in *violation* with the Arkansas River Compact, therefore they are considered as infeasible. The stream-aquifer interaction predictions are presented in three groups based on the Arkansas River and tributaries sum of RMSE in change from the baseline. The alternatives with a RMSE sum smaller than 150 acre-ft/week are placed in the *smaller* error group, and alternatives with RMSE sum larger than 250 acre-ft/week are the *larger* group, all other alternatives are in the *average* group. Similar methodology is used to classify water quality predictions for the alternatives, using the RMSE sum of the difference of salt load change from the baseline. The category *smaller* is assigned to the sum of RMSEs smaller than 300 ton/week, the *larger* category is assigned to alternatives with sum of RMSE larger than 600 ton/week and the *average* category is used for alternatives sum of RMSEs between the *smaller* and *larger* groups. The average salt concentration of the flow to Kansas is compared with the historical. Average concentration changes within 5% of the historical concentration are considered as *same*, concentration reductions of up to or equal to 10% of the historical are grouped into *good*, concentration reductions between 10% and 20% are grouped into *better*, and improvements in TDS concentration of more than 20% are categorized as *best*.

This table can guide decision making for implementation of the management alternatives and help focus efforts on future modeling refinements such as improvements in drained water modeling, return flow modeling for type of scenarios with larger errors, and longer term modeling for lower than historical end of storage alternatives.

Table 7.3 – Summary Management Alternative Performance for System Operational Mode A

Alternative Name	Water Shortages	End-of-Simulation Storage Relative to Historical	Relative Aquifer-Stream Interaction Modeling Error		Flow to Kansas (Ark. River Compact)	
			Quantity	Quality	Quantity	Quality
Drain100	Large	Empty	Average	Larger	Violation	Good
Drain150	Large	Empty	Average	Larger	Agreement	Good
Drain50	Large	Empty	Larger	Larger	Violation	Same
Drain75	Large	Empty	Average	Larger	Agreement	Good
New_rech50Seep50	Small	Lower	N/A	N/A	Agreement	Better
Pump200	None	Equal	Average	Average	Agreement	Best
Rech10	Small	Lower	Smaller	Smaller	Agreement	Same
Rech20	Small	Lower	Smaller	Smaller	Agreement	Good
Rech30	Small	Lower	Smaller	Smaller	Agreement	Good
Rech30Drain100	Large	Empty	Average	Larger	Violation	Good
Rech30Seep50	Small	Lower	Average	Average	Agreement	
Rech30Seep50Drain100	Large	Empty	Larger	Larger	Violation	Good
Rech40	Small	Lower	Smaller	Smaller	Agreement	
Rech50	Small	Lower	Smaller	Smaller	Agreement	Good
Rech50Drain50	Large	Empty	Larger	Larger	Agreement	Good
Rech50Seep90	Small	Lower	Larger	Larger	Agreement	Best
Rech50Seep90Drain50	Small	Lower	Larger	Larger	Agreement	Best
Rech60	Small	Lower	Average	Average	Agreement	Better
Rech70	Small	Lower	Average	Average	Agreement	Better
Rech80	Small	Lower	Average	Average	Agreement	Better
Rech80Drain50	Large	Empty	Larger	Larger	Agreement	Better
Rech80Seep90	Small	Lower	Larger	Larger	Agreement	Best
Rech80Seep90Drain50	Small	Lower	Larger	Larger	Agreement	Best
Rech90	Small	Lower	Larger	Average	Agreement	Better
Seep50	Small	Equal	Smaller	Smaller	Agreement	Better
Seep50Drain100	Large	Empty	Average	Larger	Violation	Good
Seep70	Small	Equal	Smaller	Average	Agreement	Better
Seep90All	Small	Equal	Average	Average	Agreement	Better
Seep90Catlin	None	Equal	Smaller	Smaller	Agreement	Same
Seep90Drain50	Small	Lower	Larger		Agreement	Better
Seep90FtLyon	None	Equal	Smaller	Smaller	Agreement	Good
Seep90Highline	None	Equal	Smaller	Smaller	Agreement	Same
Seep90Holbrook	Small	Equal	Smaller	Smaller	Agreement	Same
Seep90Lined20	Small	Equal	Average	Average	Agreement	Better
Seep90Otero	Small	Lower	Smaller	Average	Agreement	Good
Seep90RockyFd	Small	Equal	Smaller	Smaller	Agreement	Better

Reservoir Operational Mode B

In this reservoir operational mode, the baseline flows and concentrations failed to match the calibration values, contrary to the situation observed in the Mode A. The baseline calibration network, called *calibration*, in Mode B used historical storage target levels and the *baseline* case stored water using the reservoir layer balancing algorithm. The management alternatives are compared against the baseline since they will use the same storage allocation algorithm. The computed water demands for this operational mode result in the same amounts as for Mode A (see Figure 7.2).

Water Allocation and Shortages for Operational Mode B

Water shortages are summarized for this operational mode to identify alternatives that are unable to meet the water rights and river compact requirements. Figure 7.30 shows the water demand shortage per alternative. Guaranteeing the adequate water rights allocation requires that there can be no water shortages. Alternatives with significant shortages are flagged as infeasible unless additional action is taken to supply the required water. Table 7.4 lists alternatives with significant shortages in contrast to the Mode A results. All alternatives not listed in Table 7.4 exhibit zero water shortages. Comparing Table 7.4 and Table 7.2, it is evident that improvements are insufficient to render any of the alternatives in Table 7.2 as being feasible. In most cases, there is a slight increase in total shortages due to changes in return flow patterns caused by alterations in the system operation rules.

Table 7.4 – Management Alternatives with Water Shortages in Operational Mode B

Alternative Name	Water Shortage [Acre-ft]
Rech80Drain50	10557
Drain50	20901
Rech50Drain50	28811
Rech30Seep50Drain100	85461
Seep50Drain100	92853
Drain75	95170
Rech30Drain100	156393
Drain100	160524
Drain150	273136

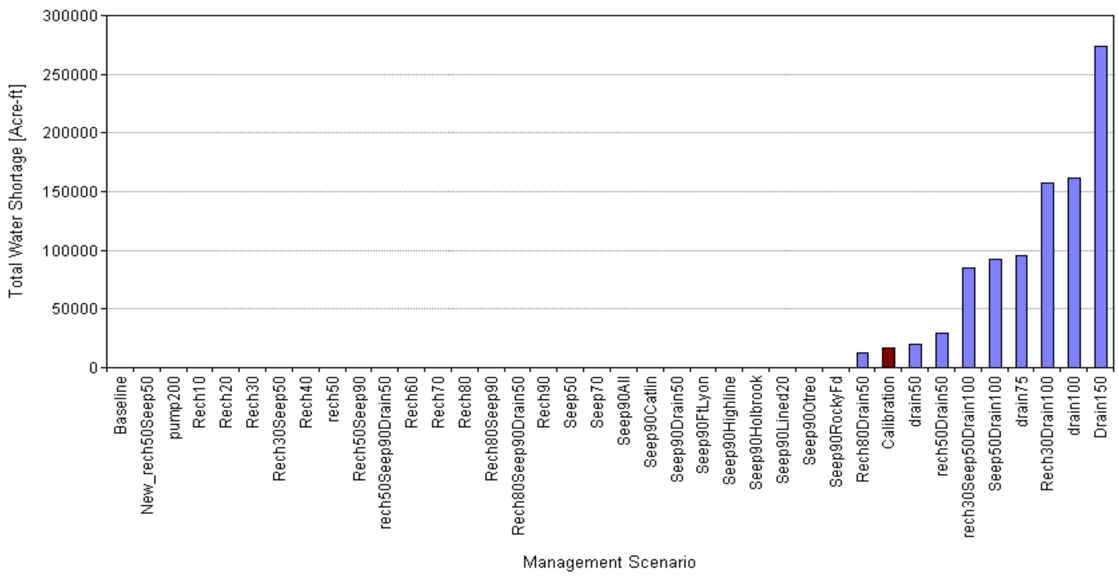

Figure 7.30 – Management alternatives water demand shortage for operational mode B for considered management alternatives

<u>Reservoir Storage and Operation for Operational Mode B</u>

In this mode the reservoir layers and costs were set so as to duplicate the historical operation. The reservoir priorities were set in such a way that all of the water demands and river compact requirements are satisfied. Since this mode allows storage above the historical storage, results should show the most efficient allocation of water by storing non-diverted water and releasing strictly the water required to satisfy water rights and the river compact. The end-of-simulation system storage for each alternative is plotted in Figure 7.31, including the baseline for comparison. As found for Mode A, alternatives with shortages show no water stored in the reservoirs at the end of the simulation, indicating the lack of enough resources in the system to make up for the changes in return flows. Table 7.5 shows the end-of-simulation storage for the alternatives, with the *additional storage* column corresponding to the difference in end-of-simulation storage between the baseline and the given alternative.

Table 7.5 – Alternatives End-of-Simulation Reservoir Storage (operational Mode B)

Alternative Name	Additional Storage [Acre-ft]	End-of-simulation Storage [Acre-ft]	Alternative Name	Additional Storage [Acre-ft]	End-of-simulation Storage [Acre-ft]
Drain100	-145192	0	Rech50Seep90Drain50	-5788	139404
Drain150	-145192	0	Rech80	-2656	142536
Drain50	-145192	0	**Baseline**	**0**	**145192**
Drain75	-145192	0	**Calibration**	**0**	**145192**
Rech30Drain100	-145192	0	Seep90Holbrook	4337	149529
Rech30Seep50Drain100	-145192	0	Rech90	8839	154031
Rech50Drain50	-145192	0	Seep90Catlin	25912	171104
Rech80Drain50	-145192	0	Seep90Highline	27123	172315
Seep50Drain100	-145192	0	Rech80Seep90Drain50	45088	190280
Rech40	-24927	120265	Rech30Seep50	53520	198712
Rech30	-24566	120626	New_rech50Seep50	58575	203767
Rech50	-22005	123187	Seep50	62388	207580
Seep90Drain50	-21107	124085	Seep90FtLyon	79419	224611
Seep90Otreo	-19487	125705	Seep70	97235	242427
Rech20	-19099	126093	Seep90All	138927	284119
Rech60	-17434	127758	Seep90Lined20	138927	284119
Rech10	-12921	132271	Rech50Seep90	150337	295529
Rech70	-11286	133906	Rech80Seep90	197779	342971
Seep90RockyFd	-9870	135322	Pump200	364534	509726

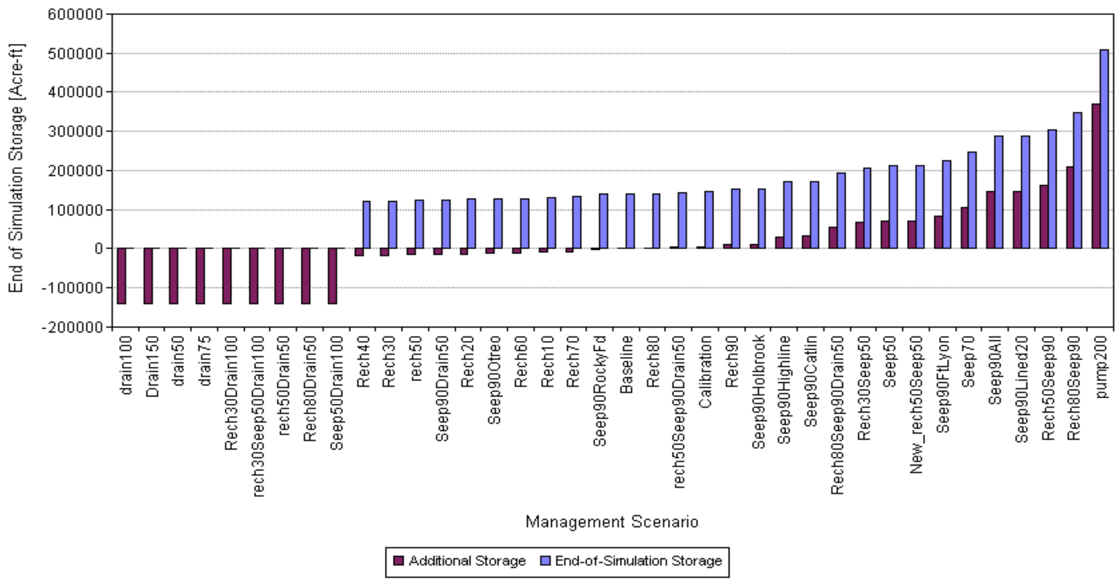

Figure 7.31 – Management alternatives end-of-simulation system storage in operational mode B

Stored water at the end of the simulation indicates that the alternative implementation produces water that can be used to further improve water quality in the system or in environmental programs and if water law allows it, provides possibilities of additional appropriation. This water could be released on-demand to reach water quality goals at selected points in the system. The possibility of storing and releasing this additional water in the actual system requires further investigation and negotiation with river administrators and system operators.

Arkansas River Compact Compliance for Operational Mode B

The Kansas flow check summary is presented in Figure 7.32. Operational mode B provides, if available, exactly the river compact requested water. This mode is able to store any additional water by releasing only what is necessary. The *Pump200* alternative is the only one that provides Kansas with additional water. This alternative includes vertical drainage water downstream of John Martin Reservoir that cannot be retained in the reservoir by exchanges for the releases. Except for alternative *Seep50Drain100*, the alternatives with zero storage at the end of the simulation (Table 7.5) violate the river compact at some point in the simulation.

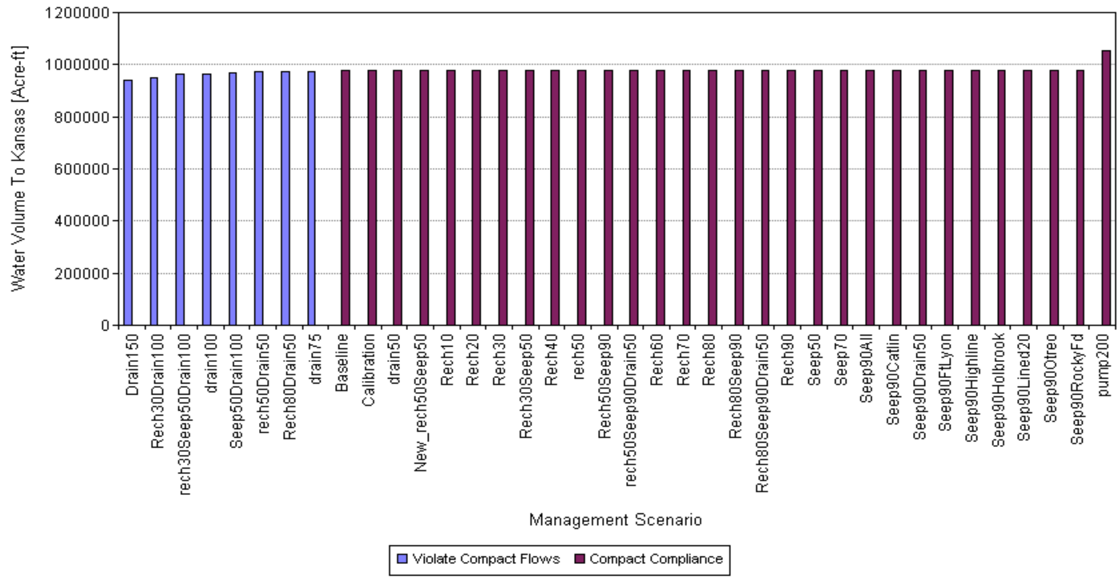

Figure 7.32 – Alternatives Colorado-Kansas state line flow in operational Mode B for considered management alternatives for considered management alternatives

Aquifer-Stream Interaction for Operational Mode B

Although, in this operational mode the modeled stream-aquifer interaction is expected to slightly change from that in Mode A due to changes in flows in the Arkansas River and in diverted water, as shown in Chapter 6, there is only a small difference in the return flow prediction between Mode A and Mode B. For practical purposes, the stream-aquifer interaction results are assumed to not change significantly in comparison to Mode A (see Figures 7.12, 7.13 and 7.14).

River Water Quality for Operational Mode B

The simulated water management alternative improvements in the system water quality at the diversion points are summarized in Figure 7.33. Comparison of the change in average diversion TDS concentrations between Mode A and B for each alternative indicate that Mode B has a tendency to provide diversion water with slightly higher concentrations than Mode A. The more concentrated diversions are caused by storing any additional water upstream in the reservoirs in Mode B, instead of releasing it to flow downstream as in Mode A. The average change in diversion concentration is 36.7 mg/L (less than 4% change from the average concentration computed in Mode A), the maximum is 109.4 mg/L and the minimum is -35.5 mg/L over all alternatives. The water management alternatives showing a decrease in the diverted concentration are: *Rech80Seep90*, *rech50Seep90Drain50*, *Drain150*, *Seep50Drain100*, *drain100*, *drain75*, *Rech30Drain100* and *Rech80Seep90Drain50.*

Figure 7.34 illustrates the simulated average TDS concentration of the water provided to Kansas. In general, results show a marginal increase in concentration as compared with the Mode A simulated concentrations. For all management alternatives with lower average TDS concentration than the baseline in Mode A, *Seep90Holbrook* is the only alternative that shows a higher concentration in Mode B. The change in average concentration between the operational modes per alternative is shown in Figure 7.35. The average change in concentration of 41.4 mg/L reiterates the overall higher concentration in the Mode B simulations as a consequence of the lower flows through out the system.

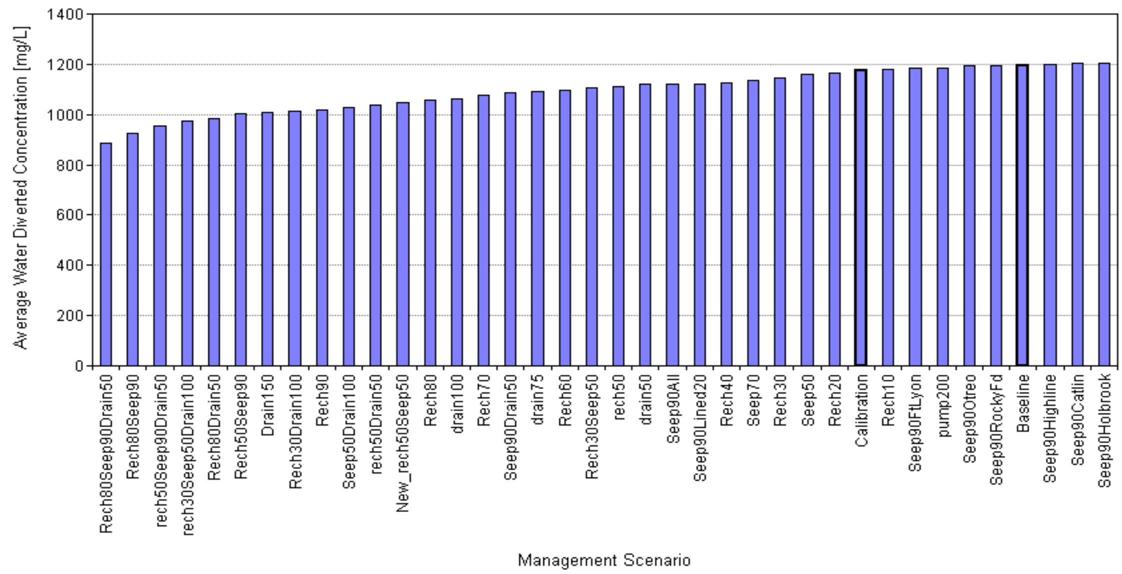

Figure 7.33 – Average TDS concentration in diverted flow per water management alternative in operational Mode B

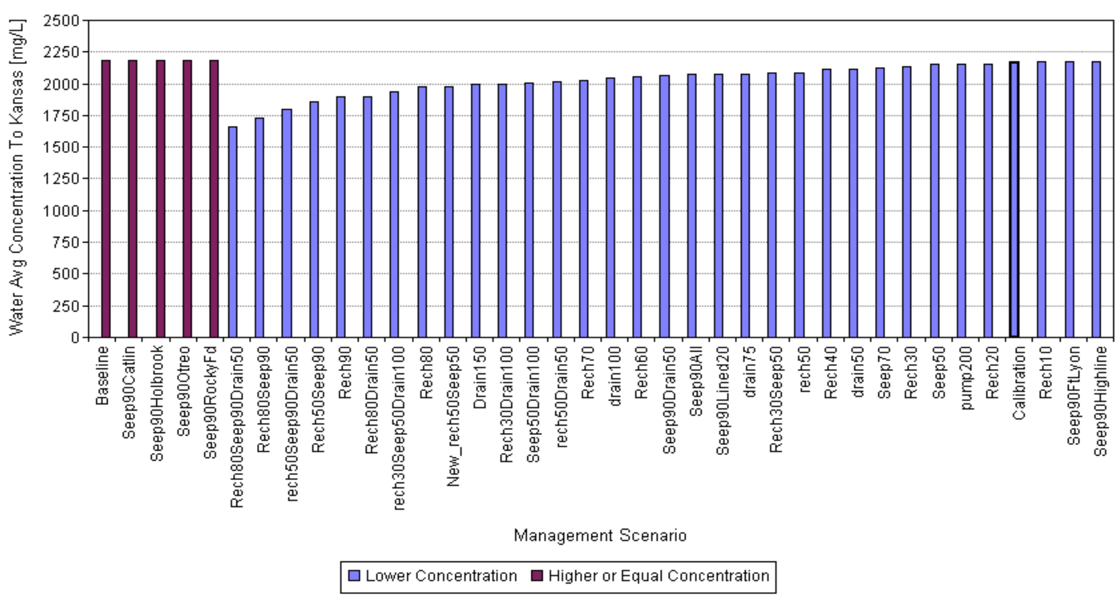

Figure 7.34 – Average TDS concentration provided to Kansas in operational Mode B for considered management alternatives

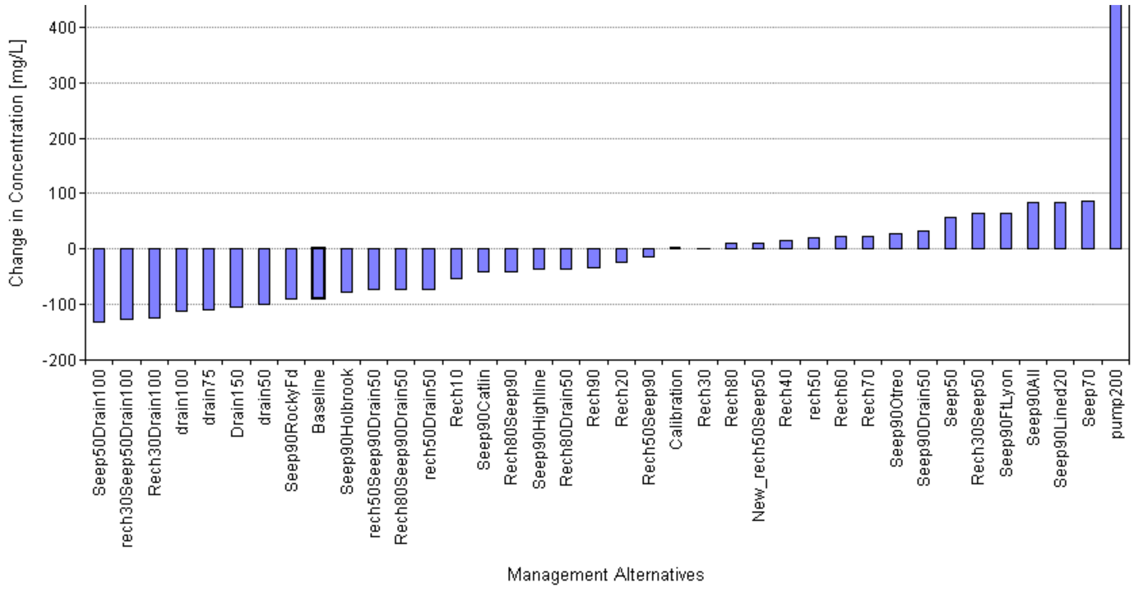

Figure 7.35 – Change in TDS concentration in flows to Kansas between Mode A and Mode B for considered management alternatives

John Martin Reservoir Salt Transport for Operational Mode B

Total predicted salt loads entering and leaving John Martin Reservoir under Mode B are presented in Figure 7.36. With the exception of *Rech80Seep90Drain50* and *Rech80Seep90*, results show a decrease in salt load from the Arkansas and Purgatoire Rivers to John Martin Reservoir. The average load reduction in the Mode B alternative is 85,080 tons. The salt released from the reservoir tends to increase by 105,483 tons on average. The average water quality transport coefficient for each management alternatives is presented in Figure 7.37. The average salt transport coefficient ($\overline{T}_r$ = 1.53) for Mode B increases slightly from the average for Mode A, most likely due to the reservoir operation reduced releases compared with Mode A. The only alternative with a transport coefficient value less than one is *Pump200*.

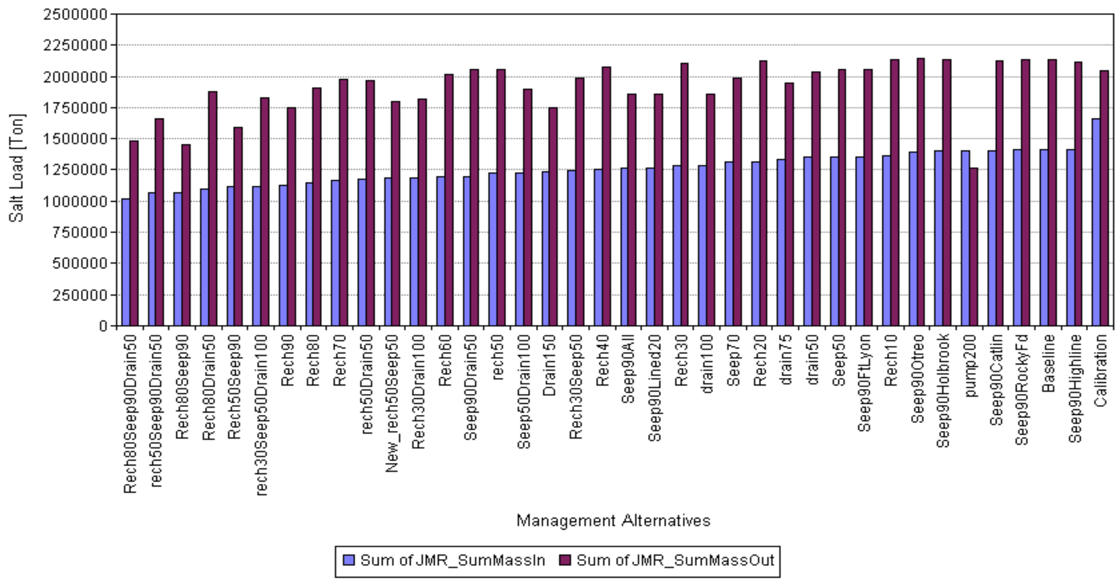

Figure 7.36 – Salt balance in John Martin Reservoir for operational Mode B for considered management alternatives

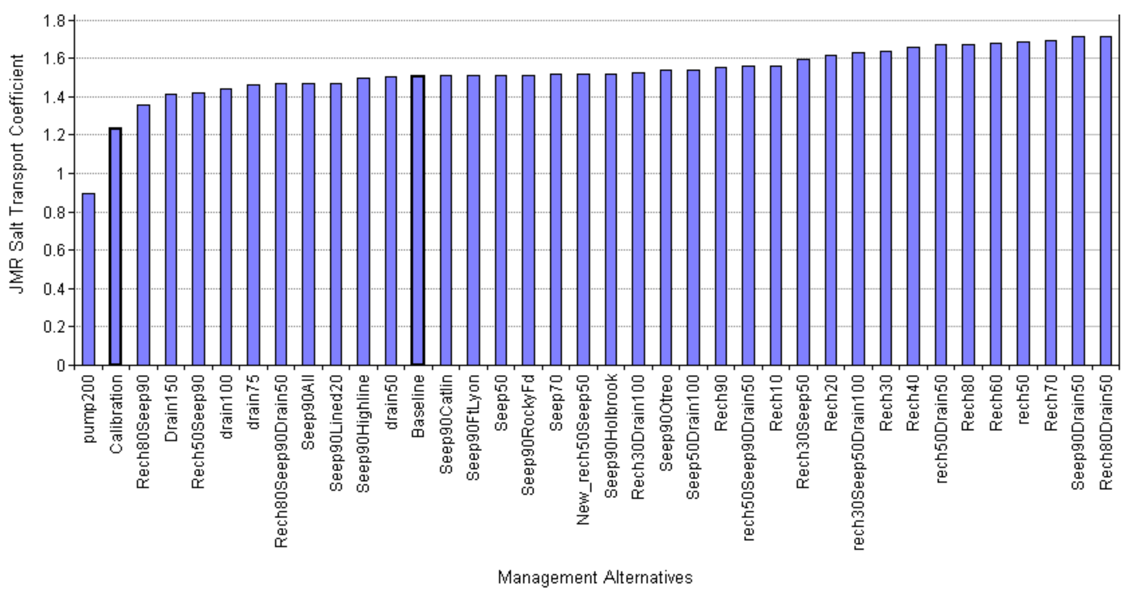

Figure 7.37 – John Martin Reservoir water quality transport coefficient for management alternatives under operational Mode B for considered management alternatives

Detailed results on system performance for all management alternatives under operational Mode B can be found in Appendix VI – *Reservoir Operational Mode B.*

Remarks on Results under Operational Mode B

The comparison of simulation results between modes A and B show marginal positive effects in the river water quality, and in some cases detrimental impacts in using Mode B reservoir operation. However, these results are expected since less water is moving downstream because it is being stored in the reservoirs. The real benefit of Mode B is in having additional end-of-simulation storage, since a potential environmental improvement could be achieved by releasing the additional water to meet water quality targets at selected locations within the basin, maximizing the effects of the water management alternatives implementation.

This reservoir modeling approach assures exact releases from the reservoirs to meet all water demands, which could result in no releases required for weeks. This situation creates problems in the water quality calibration since small or zero flows in the main stem amplify the effects of salt contributions from the tributaries, thereby making calibration more difficult. The effect of small or zero flows in the river causes spikes of high concentrations that can affect the ANN-based reservoir salt transport results. This aspect of the reservoir layer balancing approach should be addressed in future refinements of the modeling system.

Table 7.6 shows a summary of the performance of the management alternatives in relation to specified evaluation criteria. The table summarizes *large* water shortage for the simulated period when greater than 100 acre-ft. The reservoir system storage is categorized depending on the end-of-simulation storage with respect to the historical, with *empty* assigned to infeasible simulations having dry conditions in the reservoirs. Management alternatives are categorized in *violation* with the Arkansas River Compact if the simulation results are unable to provide at least the historical flows to Kansas. The average salt concentration is compared with both the historical and the operational Mode A. Average concentration changes within 5% of the historical concentration are considered as *same*, concentration reductions of up to or equal to 10% of the historical are grouped into *good*, concentration reductions between 10% and 20% are grouped into *better*, and improvements in TDS concentration of more than 20% are categorized as *best*. This table helps identify alternatives that would be more intricate to implement and alternatives with more potential for water quality improvement.

Table 7.6 – Summary Management Alternative Performance for System Operational Mode B

Alternative Name	Water Shortages	End-of-Simulation Storage Relative to Historical	Flow to Kansas		
			Ark. River Compact	Concentration relative to historical	Conc. Change From Mode A
Drain100	Large	Empty	Violation	Better	Same
Drain150	Large	Empty	Violation	Better	Same
Drain50	Large	Empty	Agreement	Good	Same
Drain75	Large	Empty	Violation	Good	Same
New_rech50Seep50	None	Above	Agreement	Better	Higher
Pump200	None	Above	Agreement	Good	Higher
Rech10	None	Below	Agreement	Same	Higher
Rech20	None	Below	Agreement	Same	Higher
Rech30	None	Below	Agreement	Good	Higher
Rech30Drain100	Large	Empty	Violation	Better	Same
Rech30Seep50	None	Above	Agreement	Good	Higher
Rech30Seep50Drain100	Large	Empty	Violation	Better	Higher
Rech40	None	Below	Agreement	Good	Higher
Rech50	None	Below	Agreement	Good	Higher
Rech50Drain50	Large	Empty	Violation	Better	Higher
Rech50Seep90	None	Below	Agreement	Best	Higher
Rech50Seep90Drain50	None	Below	Agreement	Best	Lower
Rech60	None	Below	Agreement	Good	Higher
Rech70	None	Below	Agreement	Better	Higher
Rech80	None	Below	Agreement	Better	Higher
Rech80Drain50	Large	Empty	Violation	Better	Higher
Rech80Seep90	None	Above	Agreement	Best	Lower
Rech80Seep90Drain50	None	Above	Agreement	Best	Lower
Rech90	None	Above	Agreement	Best	Higher
Seep50	None	Above	Agreement	Good	Higher
Seep50Drain100	Large	Empty	Agreement	Better	Lower
Seep70	None	Above	Agreement	Good	Higher
Seep90All	None	Above	Agreement	Good	Higher
Seep90Catlin	None	Above	Agreement	Better	Higher
Seep90Drain50	None	Below	Agreement	Good	Higher
Seep90FtLyon	None	Above	Agreement	Same	Higher
Seep90Highline	None	Above	Agreement	Same	Higher
Seep90Holbrook	None	Above	Agreement	Better	Higher
Seep90Lined20	None	Above	Agreement	Good	Higher
Seep90Otero	None	Below	Agreement	Better	Higher
Seep90RockyFd	None	Below	Agreement	Better	Higher

Analysis of Stream-Aquifer Results

The stream-aquifer interaction results need to be interpreted in the context of the MODFLOW-MT3DMS modeling, thereby analyzing the aquifer flow budget components to understand changes in the aquifer behavior under various management alternatives. MODFLOW-MT3DMS output files were processed using Geo-MODFLOW, where the flow budget components were summarized for the entire simulated area, to compare volume differences between a sample management alternative and the baseline simulation. The MODFLOW flow budget is composed of: Aquifer Storage, Wells, Rivers, Recharge, Evaporation (up-flux from the water table), Drainage, and General Heads (Seepage). Net changes in these components from the baseline simulation are examined for the water management scenario *Rech50*, which reduces irrigation-induced areal aquifer recharge by 50 percent. In this comparison, results show the following tendencies: (1) areal recharge reduction, (2) canal seepage increase, (3) reduction in upflux from the water table, (4) net return flow decrease, (5) aquifer storage decrease, and (6) no change in the pumping. Although the management scenario only includes reduction in the areal aquifer recharge, changes in the water table depth affect the system dynamics including computed canal seepage, return flow, and upflux. Figure 7.38 depicts weekly changes in MODFLOW flow budget components between the *Rech50* scenario and the baseline simulation.

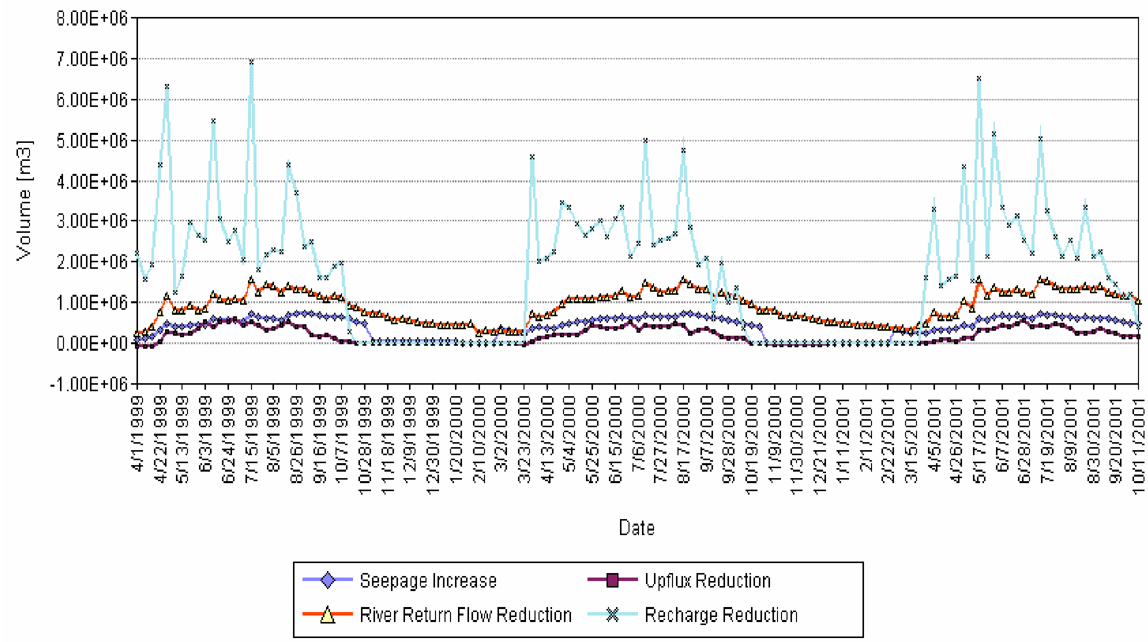

Figure 7.38 – MODFLOW Flow Budget components change for 50% areal recharge reduction alternative compared to the baseline

For understanding the changes to the groundwater system, the terms implying water additions (gains) to the baseline aquifer conditions are combined together. Components resulting in more water available to the aquifer include river return flow reductions, canal seepage increases, and the reduction in upflux from the water table. In contrast, areal recharge reduction represents less water to the aquifer (irrigation losses) during the alternative modeling. Figure 7.39 presents the comparison between the additions/subtractions to the baseline aquifer water. The difference between additions and subtractions in Figure 7.39 indicates the change in aquifer storage. The total simulated aquifer gains are 2.00×10^{8} m^3 (162,142 acre-ft) and the total simulated aquifer losses are 2.28×10^{8} m^3 (185,004 acre-ft), indicating that approximately 12% of the water lost was derived from aquifer storage depletion. Figure 7.40 shows the change in aquifer storage from the baseline storage, where positive values indicate release of water from storage and negative values represent additional water to storage. The accumulated storage over the simulated period shows that during this alternative simulation, the aquifer storage is depleted. Since the river return flows are the only dynamic component of the flow budget modeled in the basin scale modeling system, the aquifer depletion reflects a net gain of water to the surface system. Since the areal recharge reduction amounts are not diverted at the canal head gates, while the aquifer return flow reductions are less than the reduction in areal recharge, a false impression of water savings can be created.

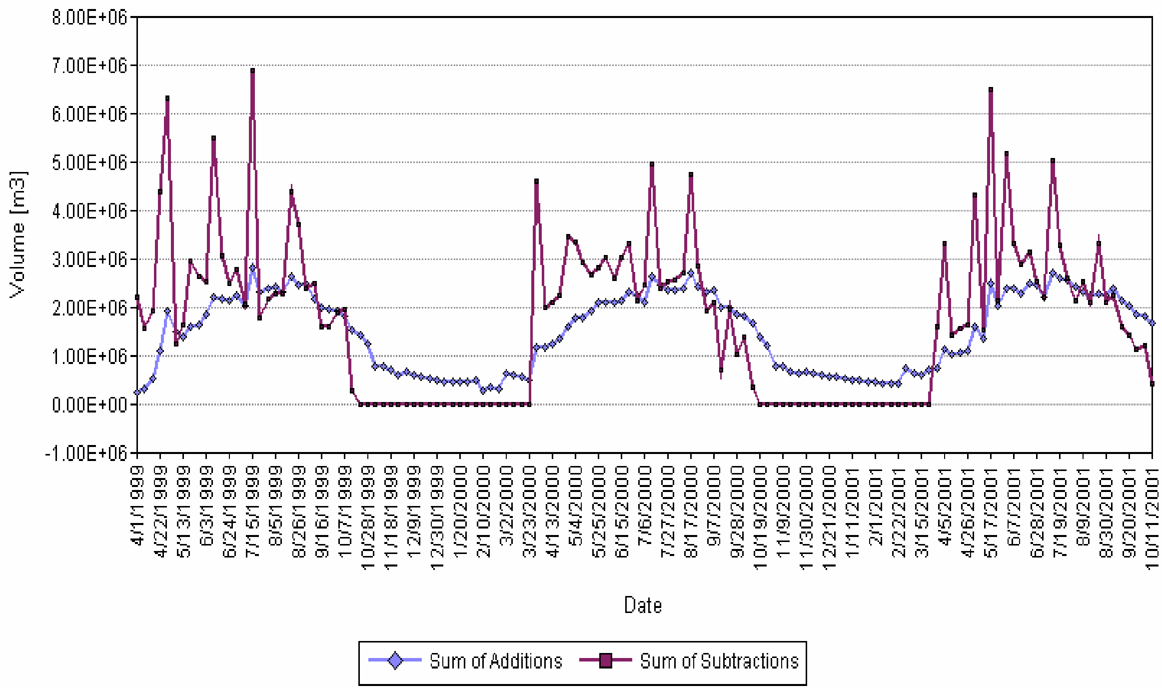

Figure 7.39 – Aquifer water balance change from the baseline conditions in Rech50 alternative

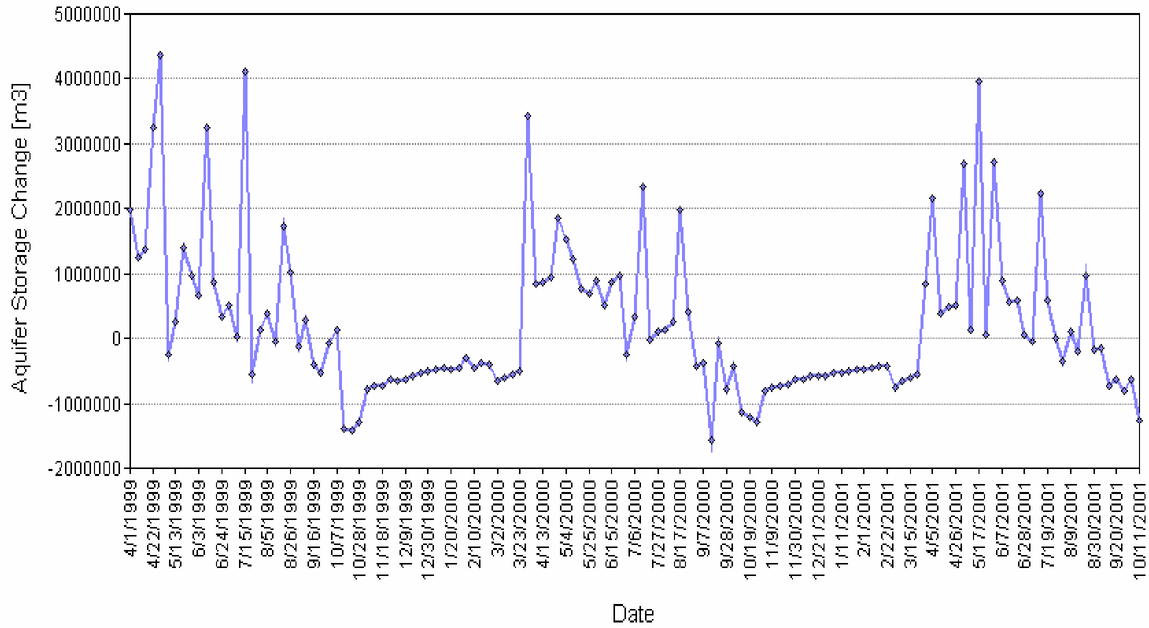

Figure 7.40 – MODFLOW Aquifer storage change from the baseline storage in Rech50 alternative

The true water savings could occur from the portion of the reduced upflux amounts located under fallowed and naturally-vegetated areas. In this alternative simulation, the simulated total upflux reduction is 25.1x10^6 m^3 (20,348 acre-ft), representing approximately 10% of the modeled recharge reduction. Assuming a uniform upflux reduction over all the fields in the modeled area, a quick approximation of the potential water saved under this scenario as a function of the aquifer recharge reduction volume can be performed using the percent of fallow fields for a given year. As an example for 2003, the percent of the fallow fields in the modeled area reaches almost 50% of the fields, potentially representing a 5% [1/2*(10%)] of the areal recharge reduction as real water savings as consequence of the alternative implementation. Current studies in the Arkansas Valley are attempting to better quantify ET from fallow and naturally-vegetated fields for better approximating actual water saved from the reduced diversion due to lowering of the water table and associated reduction in upflux to ET. Most likely, the implementation of these kinds of alternatives will drive the system to a new long-term equilibrium that might include less aquifer storage than the baseline equilibrium state. In conclusion, the simulated results for this management alternative reflect the best possible improvements in the system quality and feasibility because of aquifer storage water made available to the surface system for dilution and for meeting downstream water obligations.

In summary, the groundwater modeling results of the 50 percent reduction in areal recharge alternative reveal changes in all components of the MODFLOW-MT3DMS flow budget, even though this alternative only directly impacts the aquifer recharge. Changing the aquifer dynamics by lowering the water table has the consequence of increasing canal seepage, reducing upflux, and reducing aquifer storage. As expected, return flows are shown to decrease, but in smaller amounts than the reduction in recharge; i.e., the non-diverted water exceeds the reduction in return flows.

The canal seepage change observed in this recharge reduction alternative simulation exposes an inconsistency in the basin-scale modeling since the *LAR GeoDSS* alternative manager takes into account only changes in the modeling system explicitly stated in the alternative. Future refinements of the modeling system need to correct the canal seepage change as a consequence of indirect impacts of the management alternatives. In the current system, the assumed canal seepage affects the ANN explanatory variables. However, errors introduced by neglecting changes in canal seepage are expected to be minimal because the ANN training is based on the originally assumed seepage amounts (i.e., first pass results) that did not include the changes in seepage. The ANN is trained with a canal seepage explanatory variable that does not include the indirect adjustment. That is, since the ANN is trained to duplicate the MODFLOW-MT3DMS modeled return flows that include all components of the flow budget, the stream-aquifer interaction predictions are expected to have less error by using the originally assumed canal seepage as a fraction of the diversion. A more significant error can be expected in the diversion reduction because the increase in canal seepage requires additional diversions to overcome these additional losses. Therefore, the modeled diversion reduction is actually greater than what it should actually be.

SUMMARY OF MANAGEMENT ALTERNATIVES MODELING

Analysis of the MODFLOW-MT3DMS modeling results reveals the interrelationship between the modeling components, enhances understanding of the management alternative modeling results, and reinforces confidence in the powerful stream-aquifer representation methodology implemented in *LAR GeoDSS*. Groundwater modeling analysis of the *Rech50* alternative shows additional water available to the surface system during the basin scale simulation of the management alternatives due to aquifer depletion without representing water savings to the system. However, there is a portion of that water actually saved by reducing upflux to ET on fallowed fields and naturally-vegetated areas.

The simulation of management alternatives that were not included in the MODFLOW-MT3DMS modeled set (e.g., *new_Rech50Seep50*) illustrates the power of the implemented modeling system. The *LAR GeoDSS* modeling system is able to simulate these new management alternatives using the ANN-based stream-aquifer interaction model and the Scenario Manager functionality. Return flow predictions for these new management alternatives are checked against MODFLOW-MT3DMS modeling results of alternatives with similar characteristics, demonstrating the reasonable *LAR GeoDSS* prediction.

The results for operational Mode B demonstrate the importance of exploiting flexibility in the reservoir operations in pursuit of implementation of the management alternatives. The operational Mode A, with limited changes in the reservoir operation, shows that most of the alternatives require at least a minimum adjustment to the reservoir operation in order to be feasible. The most effective improvements in the river water quality are found in Mode B, where additional water stored at the end of the simulation indicates a greater potential to improve water quality in the system by releasing the additional water in patterns designed to meet water quality targets. In this case, additional releases during the irrigation season might have the best impact on agricultural activities by applying better quality water to the fields, with the off-season low flows potentially more concentrated. In terms of water quality improvements and reservoir storage usage, the results presented in the Mode B simulations can be considered as the worst case scenario for each of the alternatives. In the water quality aspect, the additional water stored in the reservoir should be released to further improve the simulated concentrations. The simulated reservoir storage is the maximum required since strategic releases distributed over the simulation period will reduce the storage requirements.

The inclusion of economic aspects of implementation of the proposed alternatives could enhance the analysis and the ranking of alternatives for future selection of those alternatives best suited for salinity and waterlogging remediation, river water quality enhancement, and water conservation. The study presented herein demonstrates the type of comparative analysis that is possible with the *LAR GeoDSS* modeling system and the ability to screen management alternatives that are going to be more difficult to implement because of violation of water rights and river compact or because implementation requires significant modifications to the water law and reservoir operation rules. It is important to point out that the surface drainage improvement alternatives do not consider the addition of the drained water to the surface system; therefore, some of these alternatives that violate water law could still be implemented if more detail modeling of the drained volumes is incorporated.