CHAPTER 6

RIVER GEODSS FRAMEWORK FOR THE LOWER ARKANSAS RIVER VALLEY, COLORADO

Described herein is the construction and application of the *River GeoDSS* framework to the LARV as a customized version for handling basin-specific data and characteristics, and problem-specific analysis. The *River GeoDSS* implements the full functionality of the spatial decision support system, including MODSIM tools for administrative and institutional water allocation modeling, such as water rights, the Arkansas River compact, storage water contracts and alternate points of diversion, coupled with *River GeoDSS* modules for conjunctive use water quantity and quality modeling. The objective of this *River GeoDSS* development is to build a tool to analyze the feasibility and effects of the regionally-defined water management alternatives in a heavily legal and administrative constrained system. The topics discussed in this chapter include: (a) gathering the data, (b) creating the geo-network, (c) describing the set of custom tools developed for *River GeoDSS* application in this basin, and (d) calibrating and simulating the system.

SPATIAL-TEMPORAL DATABASE

A comprehensive spatial-temporal database was developed for the LARV to support modeling, analysis and decision making tasks. The database is assembled with information from the USGS, Army Corps of Engineers, the CDWR, the NRCS and CSU field-collected and digitized data. Spatial data are compiled in ESRI® geo-databases; while, temporal data are stored in native MS-Access database format. Spatial data in the GIS platform facilitates integration and cooperation between research studies at the field, regional and basin scales. The database includes digital topography, political divisions, hydrography, hydraulic structures (e.g., canals, dams, siphons, and diversion structures), irrigated fields, Soil Survey Geographic Database (SSURGO), land use types, bed rock scatter points, aerial photos (DOQs), satellite images and spatially referenced field data. Diversion structures and reservoirs have associated water rights which are relationally joined with the GIS features. Dynamic features include measurements or characteristics varying in time, including water quantity and quality measurements in both surface and groundwater systems, climatic variables, water diversions, and groundwater pumping. Measurements are stored in database tables and relationally joined with spatially-referenced features such as gauging stations, climatic stations, diversion structures, pumping wells, and monitoring wells. NOAA–NEXRAD precipitation data are processed into raster maps and made available for the *River GeoDSS*. The database also contains processed data such as watersheds, slopes, hydrologic networks, geometric networks, and geo-referenced groundwater model results. Samples and details of the spatial-temporal database are found in Appendix V – *Spatial-Temporal Database Description*.

GEOMETRIC NETWORK

The geometric network for the *LAR GeoDSS* is based on the USGS NHD network. The network elements are filtered, processed and imported into the *LAR GeoDSS* data-model, with stream detail reduced to the major tributaries and the Arkansas River. The study region extends from Pueblo Reservoir to the Colorado-Kansas state line. Flow directions are assigned using the digitized direction, which works well for natural streams, but needs to be manually edited for canals and drains in the system. The network flow direction and connectivity rules are implemented to accurately represent the physical system water movement. Complementing information from aerial photography, a system field reconnaissance was performed in 2005 providing ground truthing for the geometric network flow and connectivity implementation. The reconnaissance visited more than 250 locations in the study area to observe hydraulic characteristics. Photographs of the visited points and observations are digitally available in the *LAR GeoDSS* database (see Appendix V – *Spatial-Temporal Database Description* for an example). The ESRI Utility Network Analyst extension was used to check connectivity of nodes and links, perform network traces and verify flow paths. Figure 6.1 shows an example of the geometric network in ArcMap, including flow directions (blue arrows) and a Utility Net Analyst downstream trace result (in red) from the XY canal diversion. These traces allow the checking of water quality mixing of flows at the canal-tributary intersections.

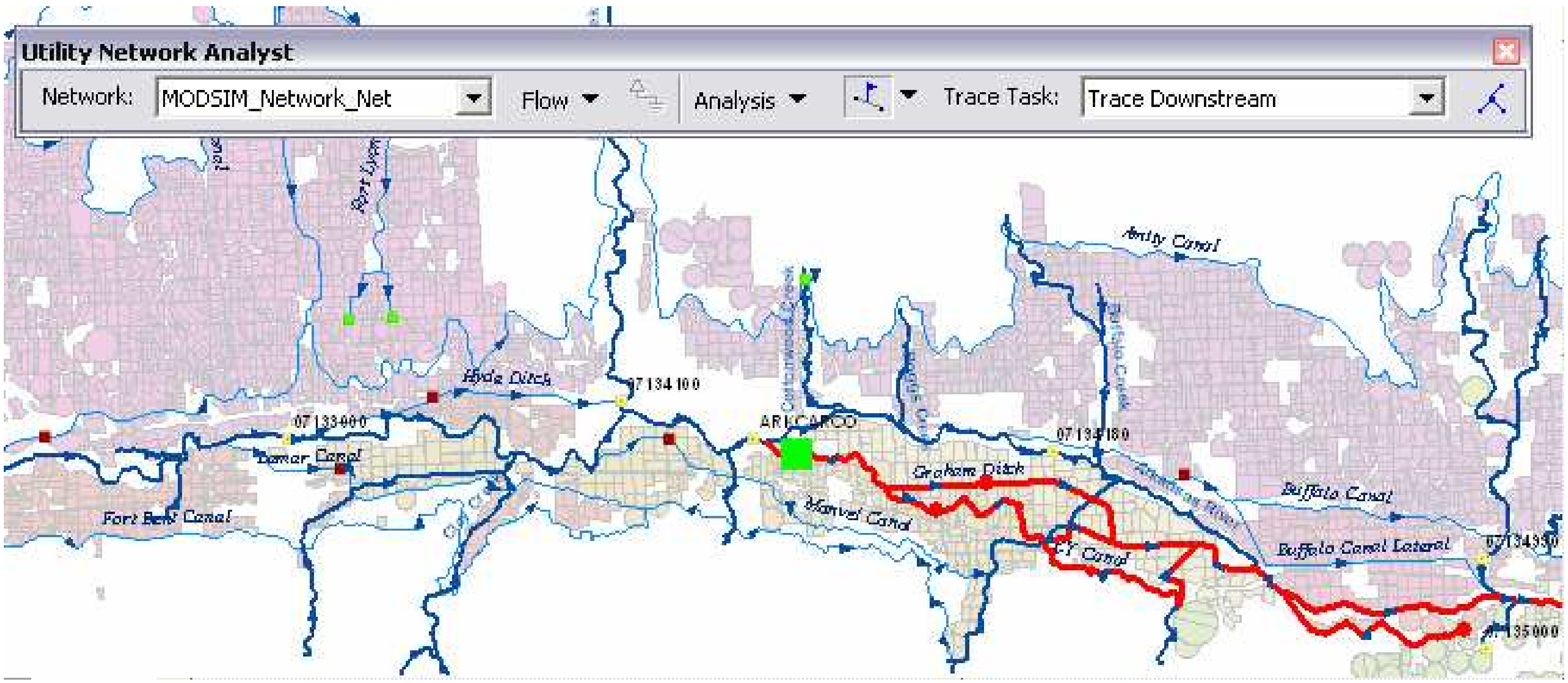

Figure 6.1 – Geometric network sample in ArcMap

GEO-MODSIM NETWORK

The Geo-MODSIM Base-Network for the *LAR GeoDSS* was generated from the geometric network. Reservoir capacities and node priorities were imported from the data-model and stored with the MODSIM Base-Network. Pueblo Reservoir and John Martin Reservoir were assigned priorities of 500 and 600, respectively, which give initial preference to water storage upstream. Gauging station demand nodes were assigned the default priority of 100, with consumptive demand nodes assigned a priority of 500. This priority scheme allows water rights to be assigned cost rankings from 0 to -5000, with a MODSIM aggregated cost of the water right link and the demand node artificial link ranging from -45000 to -50000. The demand priorities are set and saved in the data-model *MOD_Cost* field. Links were assigned the default zero cost values, except for the link connecting the Holbrook Canal diversion back to the main river and reservoir bypass links which were assigned with a positive cost of 10 to discourage use of these routes. Figure 6.2 shows the selected (bright blue) return link from the Holbrook Canal diversion that is assigned a positive cost.

The *LAR GeoDSS* employs special structures to model irrigation canal diversions as consumptive demands. The consumptive demands located close to the diversion point were modeled as *flow-through* demands with water right links immediately downstream of the node pulling water into the canal system but allowing diverted water to continue flowing to the end of the canal where it is "consumed" by the terminal interface. Flowing diverted water through the canal links allows querying and display of diverted flow anywhere in the canal, especially useful for analysis of long canals that extend for dozens of kilometers. If applicable, the terminal interface allows the return of a fraction of the diverted flow back to the river system.

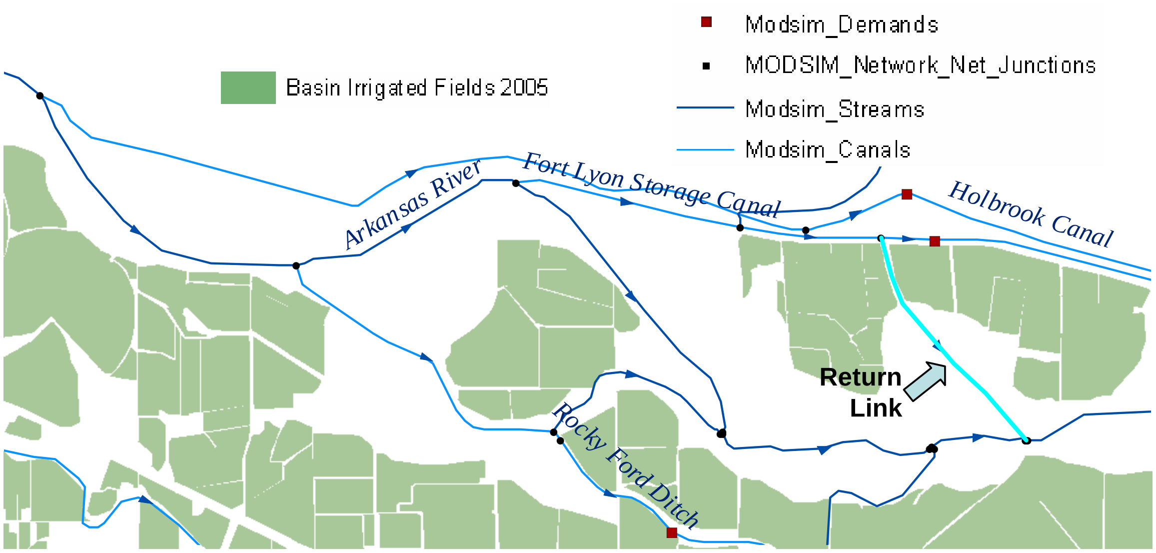

Figure 6.2 – Diversion return link example

Data obtained from Abbott et al. (1985) were used to populate the reservoir capacities in the data-model. These values were stored in the geo-database and transferred to the Geo-MODSIM network using the *River GeoDSS* interface menu item *Tools → Load data-model Data*.

CUSTOMIZED *RIVER GEODSS*

This section describes the set of customized *River GeoDSS* tools for the LARV modeling. An enhanced *River GeoDSS* interface was implemented to provide access to the custom data management and analysis tools. The custom tools include importing time series data, water rights data, and system characteristics, as well as managing and analyzing "what if" water management scenarios, and handling storage water operations and alternate points of diversion. The tools are presented in two groups, where the first group includes tools for system model assembly, and the second group consists of tools designed to handle customized analysis.

System Model Assembly

This section describes tools that are used to build and populate the *LAR GeoDSS* modeling system. Theses tools are developed to handle particular data formats, units and specific characteristics of the Arkansas River basin. Description of the underlying analysis and assumptions is also provided in this section as a reference for the appropriate utilization of these tools. Time series data in the *LAR GeoDSS* were compiled into a central database, with detail on the file structure provided in Appendix V – *Time Series Database*. The time series database is accessed by the tools described in this section, with the database location defined in the *Data Management* Interface.

Reservoir Storage System

The LARV contains two on-stream reservoirs (Pueblo Reservoir and John Martin Reservoir), and nine major off-stream reservoirs for irrigation purposes. Based on the system operation described in Abbott et al. (1985), several reservoir storage processes occur in the basin. Lake Henry and Lake Meredith, off-stream reservoirs owned by the Colorado Canal, are used to store water during the winter. The location of Lake Meredith, however, requires an exchange with the Holbrook Canal, the Fort Lyon Storage Canal, or the Arkansas River for the Colorado Canal irrigators to use the stored water. Although limited availability of historical records requires disabling these reservoirs in the *LAR GeoDSS*, exchanges in the records are modeled as storage water diversions (see "Storage Diversion and Exchanges").

The Great Plains Reservoirs [Nee So Pah (Black River), Nee No She (Standing Water), Nee Gronda (Big Water), and Nee Skah (Queens) reservoirs] are part of the Amity Canal system. These reservoirs are broad shallow lakes where the surface-area-to-capacity ratio produces significant evaporation losses. Since a large dead-storage pool permits more stored water than can be withdrawn, storage for the Amity Canal is maintained in John Martin Reservoir whenever possible. Since no records are found for diversion from these reservoirs, they were disabled in the current version of the *LAR GeoDSS*.

The Holbrook Canal can store water in Holbrook Reservoir, but this reservoir is unable to deliver water to the irrigated lands and requires an exchange with the river to use stored water. Diversion records for Holbrook Reservoir are only available for dates prior to 1983, thereby limiting the modeling of storage in this reservoir. Storage water records were used to model water exchanges.

The Fort Lyon Storage Canal delivers water to Horse Creek Reservoir and Adobe Creek Reservoir, with the ability of releasing irrigation water directly to the Fort Lyon Canal. Since these reservoirs have negligible impact on the entire system operation and because of the lack of readily available data, therefore they were disabled in the *LAR GeoDSS*.

Flow Data

Flow data at gauging stations in the Arkansas River Valley are available from the USGS and CDWR. The raw daily data were stored in the time series database, where the current database includes USGS data ranging from 1912 to September 2004 and CDWR data from 1935 to December 2003 for a total of 24 stations in the river basin. Table 6.1 and 6.2 provide a summary of the active gauging stations available in the database as well as their periods of record and average flow.

Table 6.1 – CDWR Gauging Stations Summary

Name	HydroCode	DataFrom	DataTo	Values Count	Average (cfs)
ARKANSAS RIVER NEAR CARLTON @ X-Y DITCH DAM	ARKCARCO	10/1/1999	9/30/2003	2557	175.12
ARKANSAS RIVER NEAR NEPESTA	ARKNEPCO	10/1/1935	9/30/2003	26571	672.52
ARKANSAS RIVER NEAR ROCKY FORD	ARKROCCO	10/1/1999	9/30/2003	2557	270.15
CROOKED ARROYO NEAR SWINK	CANSWKCO	2/1/1968	9/30/2003	13957	12.05
HORSE CREEK AT HIGHWAY 194	HRC194CO	10/1/1979	9/8/2003	8232	17.17
PURGATOIRE RIVER AT NINEMILE DAM, NEAR HIGBEE (C	PURNICCO	1/1/1998	9/25/2003	2019	71.28
PURGATOIRE RIVER BLW HIGHLAND DAM NR LAS ANIMAS	PURHILCO	5/23/2001	9/22/2003	643	28.49
ARKANSAS RIVER AND CATLIN CANAL (COMBINED)	ARKCACCO	1/1/1998	9/30/2003	2098	657.45

Table 6.2 - USGS Gauging Stations Summary

Name	HydroCode	DataFrom	DataTo	Values Count	Average (cfs)
APISHAPA RIVER NEAR FOWLER	07119500	4/1/1922	9/30/2004	25511	20.48
ARKANSAS RIVER ABOVE PUEBLO	07099400	10/1/1965	9/30/2004	14610	602.41
ARKANSAS RIVER AT LA JUNTA	07123000	4/1/1912	9/30/2003	33778	240.33
ARKANSAS RIVER AT LAMAR	07133000	6/1/1913	9/30/2004	32385	183.10
ARKANSAS RIVER AT LAS ANIMAS	07124000	6/1/1939	9/30/2004	24229	236.37
ARKANSAS RIVER AT MOFFAT STREET AT PUEBLO	07099970	10/1/1988	9/30/2004	6209	565.81
ARKANSAS RIVER BELOW JOHN MARTIN RESERVOIR	07130500	4/1/1938	9/30/2004	24443	332.65
ARKANSAS RIVER NEAR AVONDALE	07109500	5/1/1939	9/30/2004	19388	848.00
ARKANSAS RIVER NEAR GRANADA	07134180	12/5/1980	9/30/2004	9066	213.97
BIG SANDY CREEK NEAR LAMAR	07134100	2/1/1968	9/30/2004	8951	18.25
FOUNTAIN CREEK AT PUEBLO	07106500	1/1/1922	9/30/2004	23022	137.46
FOUNTAIN CREEK NEAR PINON	07106300	4/1/1973	9/30/2004	11221	154.75
HUERFANO RIVER NEAR BOONE	07116500	1/1/1922	9/30/2004	8712	43.44
PURGATOIRE RIVER NEAR LAS ANIMAS	07128500	1/1/1922	9/30/2004	24406	79.21
SAINT CHARLES RIVER AT VINELAND	07108900	10/1/1978	9/30/2004	9862	39.93
TIMPAS CREEK AT MOUTH NEAR SWINK, CO.	07121500	1/1/1922	9/30/2004	15097	58.18
TWO BUTTE CREEK NEAR HOLLY, CO.	07135000	6/9/1942	8/3/1999	59	39.31
ARKANSAS RIVER NEAR COOLIDGE, KS	07137500	1/1/1998	9/30/2003	2099	345.30
CHICO CREEK NEAR PUEBLO CHEMICAL DEPOT	07110400	1/1/1998	9/30/1999	612	7.35
WILD HORSE CREEK ABOVE HOLLY	07134990	3/18/1998	9/30/2004	1612	20.89

Diversion records for all water users in the basin are maintained and provided by the CDWR, with daily diversion records included in the *LAR GeoDSS* time series database. The records include flags and user id to track regular diversions as well as storage water and alternate points of diversion. The database includes more than 300 water users with water use records ranging over the period 1910 to 2004.

Reservoir storage data are maintained by the US Army Corps of Engineers, Albuquerque District, and the USBR. The USBR makes available the Pueblo Reservoir daily data through the *HydroMet* database, and storage levels from 1999 to 2005 were stored in the *LAR GeoDSS* time series database. John Martin Reservoir data were downloaded from the US Army Corps of Engineers web page and complemented with data from 1970 to 1991 as provided by the Albuquerque District personnel.

Gauging Stations

Flow data at the gauging stations represent inputs or check points along the system. The most upstream gauging stations in the network were used as network sources, with intermediate stations used in calibration to quantify local gains and losses. The measured flows were loaded into the corresponding demand node time series, where the system source nodes, modeled as *flow-through* demand nodes, request the measured flow from the calibration structure and convey the flow downstream. Intermediate control points regulate the automatic calibration of the network and can be used for comparison of simulated flows with the baseline network during simulation of the management alternatives.

Diversion Water

Historical diversion records were used to populate the water demand time series data sets according to the modeled time step. Daily values were extracted, using the CDWR Water Bank Codes (described in Appendix V). In this application, these daily flows were then summed to weekly volumes for modeling purposes.

The diversion data for certain water users required special handling since these users were under a different water district subsequent to water year 1999 (Table 6.3). This situation is identified by users having the same structure ID and user name under different water district (WD) numbers. Diversion records for these users associated with WD 14 extend through water year 1999, and then are associated with water district 17 thereafter. CDWR personnel expressed that in this situation, where both water districts have records and the data are expected to be duplicated, data for only one of the water districts is required for processing in the *LAR GeoDSS*.

Table 6.3 – Three Digit Structures with Data under Different WD Numbers

ID	WD Nos.	NAME
540	14, 17	COLORADO CANAL
542	14, 17	ROCKY FORD HIGHLINE
558	14, 17	ROCKY FORD DITCH
652	14, 17	LAS ANIMAS TOWN DITCH
659	14, 17	COLO CANAL RETURN FLOWS

Reservoir Storage Data

Even though all major reservoirs in NHD dataset were included in the geometric network, only the on-stream Pueblo and John Martin Reservoirs in the LARV have readily available measurements of historical daily volumes, inflows and outflows to populate storage target time series and be modeled as standard MODSIM reservoir. Off-stream reservoirs were modeled based on the storage water diversion records as discussed subsequently under "Storage Water Diversion and Exchanges". For calibration purposes, reservoir storage targets were set to the historical measured volumes in the reservoirs. For simulation of management alternatives, two reservoir modeling modes were tested: (1) historical storage was used as the target storage level and (2) reservoir layers were used to balance the system storage between the active reservoirs (described in detail in Chapter **7** – *Reservoir Operational modes*).

Time Series Import Tool

The *LAR GeoDSS Time Series Import* tool processes the daily flows stored in the database according to the modeled time step and units. The tool imports: (1) the processed gauging station flow data into the corresponding *flow-through* demand nodes that represent the gauging stations, (2) measured diversions into the corresponding consumptive use demands, and (3) historical reservoir storage levels as reservoir targets and reservoir initial volumes for the corresponding simulation start date.

The tool is accessed as a menu item in: *Arkansas Tools→Populate Time Series→All Historical.* The tool allows importing time series for all existing nodes in the network or for a selected node from a list. A zero value is used to fill missing daily data, indicating no flow contributions for these time steps.

The reservoir initial volume entries are populated with the historical reservoir volumes at the beginning of the simulation period, and the target volumes are assigned as historical storage levels at the end of each time step.

Precipitation Data

Spatial precipitation data were processed into the *LAR GeoDSS* using raster maps generated by two methods: (1) NEXRAD Stage III data and (2) spatially interpolated climate station measurements.

NEXRAD Stage III employs operational hourly rain gauge data, and interactive quality control by Hydrometeorological Analysis and Service (HAS) forecasters at the National Weather Service River Forecast Centers to produce the Digital Precipitation Array (DPA) products. DPA products are generated by the Precipitation Processing Subsystem (PPS), which is one of many automatic algorithms in the WSR-88D Radar Product Generator (Fulton et al. 1998). Radar-based NEXRAD Stage III spatial precipitation data were collected from National Oceanic and Atmospheric Administration (NOAA) Hydrologic Data Systems for the LARV from 1997 to 2005. The downloaded hourly data were processed and compiled into daily raster maps using a *River GeoDSS* utility for accumulating precipitation according to the modeled time steps. Figure V-6 (in Appendix V) shows a sample of the resulting weekly-precipitation raster map.

Both the NWS and CoAgMet maintain climate stations that were utilized for this project. Since the climate stations provide point-based precipitation in the Valley, the *River GeoDSS* implements a utility (Figure 6.3) to generate spatial precipitation raster maps from the point-measured values. This utility uses the time series database data and file preferences in the *River GeoDSS Data Management* Interface (Figure 3.3). The station points are assigned the measured values and simple spatial interpolation (using the inverse distance weighting (IDW) method) is performed to generate sets of raster precipitation maps. In addition to simplifying automation, IDW introduces smaller errors on estimates of climatic discontinuous phenomena such as precipitation, than other spatial interpolation methods with smoothing effects (e.g., Kriging) (Brown and Comrie 2002). Figure 6.4 shows an example of the weekly spatial interpolated precipitation and the stations used in the processing.

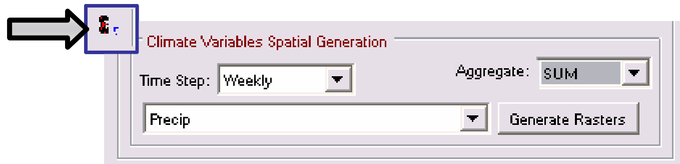

Figure 6.3 – Spatial Climate variables generator utility interface

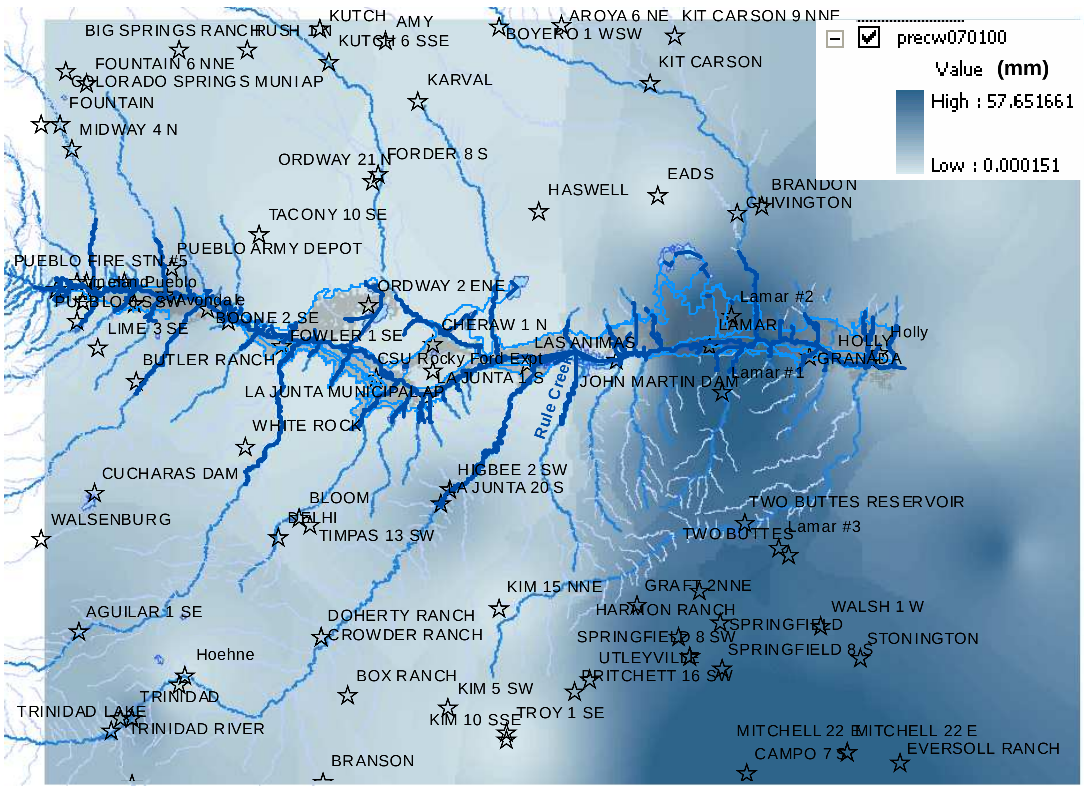

Figure 6.4 – Spatial precipitation interpolated from point-based measurement
(location indicated by ☆)

Precipitation summary databases were created using a *LAR GeoDSS* utility (Figure 6.5) that implements the ArcGIS *zonal statistics* function for the user-specified zones. This utility generates tables of precipitation statistics for the specified zones (e.g., polygons, lines or points) for each modeled time step. The utility uses *LAR GeoDSS Data Management* Interface preferences for output database names and locations. Currently, precipitation data are exclusively used as an ANN explanatory variable in the stream-aquifer interaction modeling. For ANN training, the regional-scale groundwater model time steps were used based on 52 weeks per year starting on April 1st. The corresponding weekly precipitation raster maps and summary tables were created starting on April 1st for the modeled years. The *LAR GeoDSS* simulations with the ANN-based stream-aquifer interaction relied on previously-generated precipitation summary tables labeled with the time step starting date. Since MODSIM time steps are continuous and uniform from the model start date, the *LAR GeoDSS* run requires the generation of slightly shifted raster maps and summary tables beginning with the second year of simulation. As a consequence, the precipitation summary database contains tables for both MODFLOW-MT3DMS and MODSIM time step start dates.

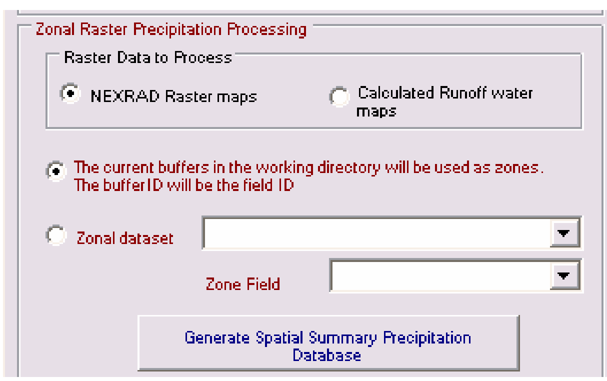

Figure 6.5 – Precipitation summary database generation utility interface

Water Quality Data

A *LAR GeoDSS* water quality database stored measured specific conductance values downloaded from the USGS collected between 1963 and 2005. Specific conductance of the samples were collected in two modes: (1) regular intervals (e.g., 15 min, 30 min), and (2) irregular intervals (i.e., grab samples). The database includes both sample modes using a type id to flag them. Table 6.4 shows a summary of the stations, the type of data collected, the number of samples available, and the earliest and latest sample in the record.

Table 6.4 – Water Quality Measuring Stations Summary

Name	Station ID	Data Type	Data Count	From Date	To Date
APISHAPA RIVER NEAR FOWLER	7119500	Regular	462	11/26/1963	05/07/2003
ARKANSAS RIVER ABOVE PUEBLO	7099400	Irregular	6809	04/01/1986	09/30/2005
ARKANSAS RIVER ABOVE PUEBLO	7099400	Regular	294	10/15/1965	09/28/2005
ARKANSAS RIVER AT LA JUNTA	7123000	Regular	91	10/20/1961	09/12/2005
ARKANSAS RIVER AT LAMAR	7133000	Regular	556	11/27/1963	09/08/2003
ARKANSAS RIVER AT LAS ANIMAS	7124000	Irregular	6422	12/04/1985	09/30/2005
ARKANSAS RIVER AT LAS ANIMAS	7124000	Regular	977	11/06/1945	09/20/2005
ARKANSAS RIVER AT MOFFAT STREET AT PUEBLO	7099970	Irregular	5434	10/05/1988	09/30/2005
ARKANSAS RIVER AT MOFFAT STREET AT PUEBLO	7099970	Regular	119	10/24/1988	09/07/2005
ARKANSAS RIVER BELOW JOHN MARTIN RESERVOIR	7130500	Irregular	6892	12/05/1985	09/30/2005
ARKANSAS RIVER BELOW JOHN MARTIN RESERVOIR	7130500	Regular	1291	10/09/1945	09/20/2005
ARKANSAS RIVER NEAR AVONDALE	7109500	Irregular	7081	07/31/1979	09/30/2005
ARKANSAS RIVER NEAR AVONDALE	7109500	Regular	916	02/04/1969	09/14/2005
ARKANSAS RIVER NEAR COOLIDGE, KS	7137500	Irregular	1896	10/01/1999	09/30/2005
ARKANSAS RIVER NEAR COOLIDGE, KS	7137500	Regular	687	11/27/1963	08/28/2003
ARKANSAS RIVER NEAR GRANADA	7134180	Regular	253	02/21/1919	09/08/2003
BIG SANDY CREEK NEAR LAMAR	7134100	Regular	281	02/07/1968	09/08/2003
CHICO CREEK NEAR PUEBLO CHEMICAL DEPOT	7110400	Regular	44	04/28/1997	01/19/2000
FOUNTAIN CREEK AT PUEBLO	7106500	Regular	700	11/26/1963	09/08/2005
FOUNTAIN CREEK NEAR PINON	7106300	Regular	715	04/17/1973	07/21/2005
HUERFANO RIVER NEAR BOONE	7116500	Regular	311	04/01/1976	06/06/2003
PURGATOIRE RIVER NEAR LAS ANIMAS	7128500	Regular	667	12/20/1961	09/09/2003
SAINT CHARLES RIVER AT VINELAND	7108900	Regular	400	11/05/1971	09/06/2005
TIMPAS CREEK AT MOUTH NEAR SWINK, CO.	7121500	Regular	454	03/14/1967	07/01/2003
TWO BUTTE CREEK NEAR HOLLY, CO.	7135000	Regular	2	08/07/1997	08/13/1997

The *River GeoDSS Water Quality Import* tool (Figure 3.14-B) was used to process and transfer the downloaded data into the network objects, with both regular and irregular data imported (see Appendix III – *River GeoDSS Water Quality Import Tool* for details and data type analysis).

Calibration Concentration Range

Field data collection in the Arkansas River Valley provided information for setting the range of valid concentrations for water quality calibration. The *LAR GeoDSS* implements a utility to guide the selection of this concentration range. The utility uses the database to present the user with maximum and minimum measured values at selected points in the system. The user can also group observed concentration values based on the types of water bodies where the measurements were taken. The types implemented in the database for this purpose are: (1) River, (2) Small Tributary (NHD level 4), (3) Large Tributary (NHD Level 3), (4) Reservoir, (5) Canal, (6) Drain, and (7) Lateral. In addition, the user can query maximum and minimum values imported into the node concentration time series data. Lastly, the user can manually enter the concentration values to be used as upper and lower limits. Figure 6.6 shows the user interface for this utility to guide the setting of calibration concentration limits. This utility can be accessed for a single gauging station (Figure 3.12) or can be used to set default values for all nodes in the system (accessed through the menu item: *Tools→Calibration Concentration→Set Defaults (Min/Max)*).

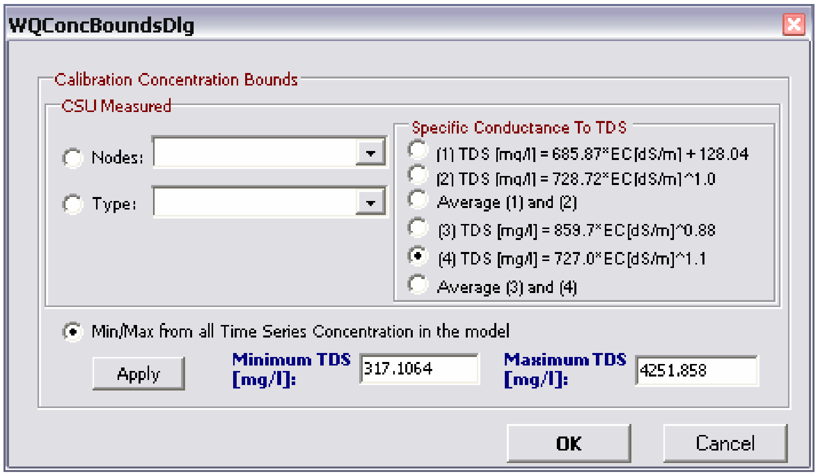

Figure 6.6 – Calibration concentration bounds guide utility interface

Table 6.5 shows a summary of the maximum and minimum values for the USGS measurements and the different types of system objects for the CSU field measurements.

Table 6.5 – Measured Concentration Limits by Measured Water Body Type

Measured Object Type	Minimum TDS [mg/L]	Maximum TDS [mg/L]
Canal	172.90	3272.50
Drain	250.78	1143.955
Large Tributary (Level 3)	477.19	2035.77
Lateral	283.63	904.75
Reservoir	280.55	975.97
River	223.69	4072.89
Small Tributary (Level 4)	307.65	2748.42
USGS Measured Time Series	317.10	4251.86

In this case study, the allowable concentration range for calibration of unmeasured flows was set basin-wide between 0 and 4500 mg/L to provide flexibility for diluting or concentrating water in the reach according to the downstream measurements. This concentration adjustment includes compensation for groundwater return flow over/under predictions.

Concentration and Flow Relationship

Cain et al. (1987) developed log-log streamflow-specific conductance equations for the Arkansas River basin, Colorado, such as log specific conductance predicted as a function of log streamflow. The same equation form was used for all stations, and accommodates bi-seasonal relationships from May through September and from October to April. The relations developed for 19 Arkansas River and 50 tributary stations explain between 12 and 88 percent of the variation in the data. A regionalization approach was used to estimate the bi-seasonal equation coefficients for stations with insufficient data for estimating the coefficients. In this case, coefficients were estimated using regression equations of the drainage area, mean annual precipitation at the station, percent of the drainage area that is irrigated, and percent of the drainage area that is underlain by shale bedrock.

In the *LAR GeoDSS*, concentrations were computed for stations with irregular measured concentration as a function of the measured flow using a fitted regression equation individually developed for each station. These regression equations allow concentration to be predicted as a function of time step flow for filling periods that lack measured concentrations. During simulation, the flow-concentration relationships were used for all time steps, regardless of the measurement availability. The regression equations generate changes in concentration due to changes in flow during the modeling of management alternatives. Appendix V contains details on the basic flow-concentration relationships developed for the *LAR GeoDSS* to estimate concentrations at stations with missing data. Table 6.6 summarizes the regression equations and station information for the irregular measured stations.

Table 6.6 – Regression Equation Summary of Irregular Sampling Stations

Station Name	MODSIM Name	Period Available	Samples Available	Regression Equation (x= weekly Flow [Acre-ft])	r^2
SAINT CHARLES RIVER AT VINELAND	STCHARCO	1978 – 2004		Conc=(3384.86)+(-345.28)*log(x)	0.69
HUERFANO RIVER NEAR BOONE	HUEBOCO	1979 – 2003	264	Conc=(4431.61)+(-417.77)*log(x)	0.70
APISHAPA RIVER NEAR FOWLER	APIFOWCO	1963 – 2003		Conc=(5360.23)*x^(-0.26942)	0.80
CHICO CREEK NEAR PUEBLO CHEMICAL DEPOT *	CHICRECO	1997 – 2000		Conc=exp((-.00267)*x+(7.11166))	0.66
TIMPAS CREEK AT MOUTH NEAR SWINK,CO	TIMSWICO	1967 – 2003		Conc=(10757.5)*x^(-0.30695)	0.82
ARKANSAS RIVER AT LA JUNTA *	ARKLAJCO	1961 – 2002	73	Conc=(3455.02)+(-285.51)*log(x)	0.88
PURGATOIRE RIVER NEAR LAS ANIMAS	PURLASCO	1961 – 2003	635	Conc=(4245.14)+(-332.65)*log(x)	0.62
ARKANSAS RIVER AT LAMAR	ARKLAMCO	1963 – 2003	510	Con=(4717.8)+(-355.25)*log(x)	0.69
BIG SANDY CREEK NEAR LAMAR	BIGLAMCO	1968 – 2003	262	Conc=exp((-.29e-3)*x+(8.10988))	0.52
ARKANSAS RIVER NEAR GRANADA	ARKGRACO	1981 – 2003	248	Conc=(5149.67)+(-347.61)*log(x)	0.73
FOUNTAIN CREEK AT PUEBLO	FOUPUECO	1963 – 2004	584	Conc=(3386.25)*x^0.1671	0.82

*Small number of data points

Water Rights

The Prior Appropriation Doctrine governs the amount of water that can be diverted at each diversion point in the Arkansas River basin. The Appropriation Doctrine establishes the amount and, in some cases, the timing in which the water can be diverted. The ability to divert water is based on the appropriation date of the right, i.e., the older the date, the higher the priority. At any given point in time, the original rights may have been modified in several ways. The final rights are the result of many transactions and decrees, which makes their determination an unwieldy task. The *LAR GeoDSS* implements a tool that, together with the MODSIM water rights extension, provides processing of the water rights database maintained by the CDWR for creation of the LARV water rights in the Geo-MODSIM network. The *LAR GeoDSS Water Rights Import* tool is accessed from the menu item *Arkansas Tools→Water Rights→Load from DB.* The tool requires a local copy of the CDWR water rights database in MS-Access database format. Figure 6.7 shows the MODSIM water rights extension interface with a sample of the imported water rights for the *LAR GeoDSS*. The text in the interface *Notes* column is generated during the import process with information on the processed transactions used to compute the final imported amount. The water rights extension creates the water rights modeling links associated with the imported rights directly into the Geo-MODSIM network, with each water right represented by a link conveying flows to the demand node representing the water user. Details about the CDWR water rights database, the import tool and its application to the *LAR GeoDSS,* as well as a summary of the processed water rights, are available in *LAR GeoDSS* user support (Appendix V – *Importing Water Rights from the CDWR Database*).

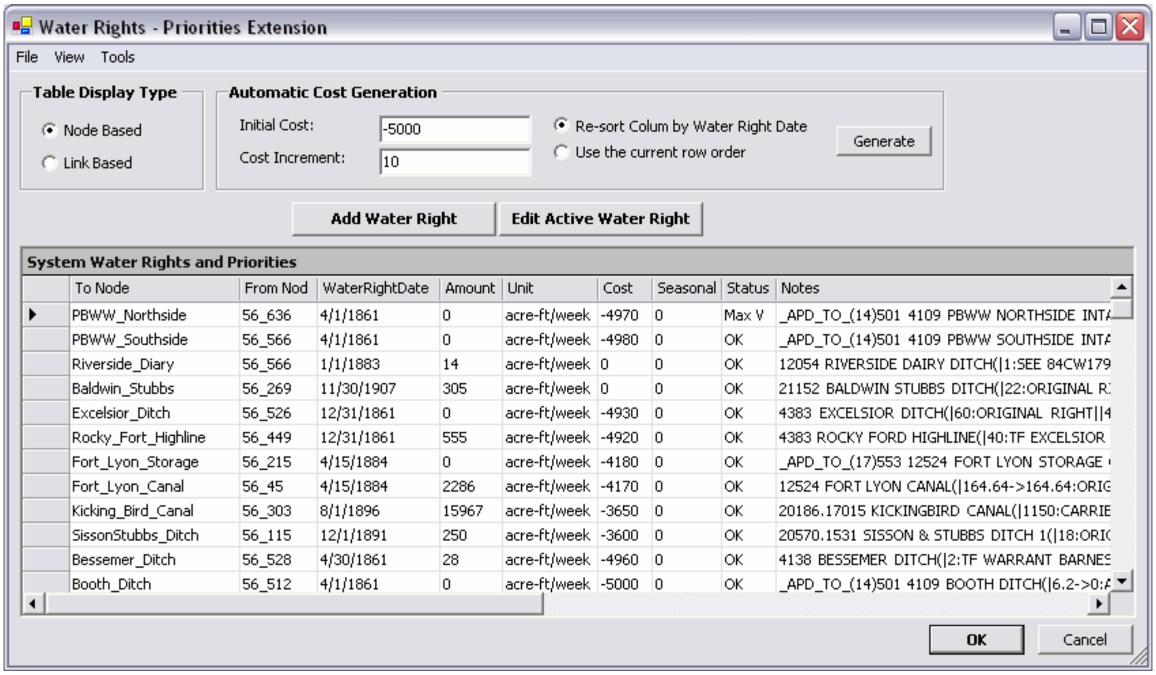

Figure 6.7 – MODSIM Water Rights Extension for the *LAR GeoDSS*

Alternate Points of Diversion

Alternate Points of Diversion (APD) are conditional diversion points in the basin where the original water right holder can take a portion of their right up to a decreed amount. The APD amounts and locations were modeled in the *LAR GeoDSS* using the historical diversion records. Since the diverted amounts at the APD were modeled as upper bounds on the high priority links that guarantee allocation of the APD diversions, the original right was consequently reduced by the amount diverted at the APD. The implementation of the APD in the *LAR GeoDSS* was automated by two utilities that build the modeling links and assign their link capacity time series from the diversion records database. The tools are accessed using the menu items: *Arkansas Tools→Create Network Links from Diversion DB→Alternate Points of Diversion* and *Arkansas Tools→Populate Time Serie→Fix Capacity to Alternate Pts of Diversion* respectively. The *LAR GeoDSS* allows the APD creation algorithm to be executed only once for each Base-Network to avoid processing errors by double counting the APD in the original rights. These tools use information coded into the link description by the import tool to associate water rights information with the diversions database. The APD active modeling links were renamed using the following format: "*ToNode* _APD_TO_(*WD*)*ID*". Table 6.7 summarizes the APD modeled in the *LAR GeoDSS*, where Table 6.7-A contains the links created during the diversion database analysis (i.e., not identified during the water rights import operation) and Table 6.7-B presents the links created during the water rights import process that are used in the APD modeling. Table 6.8-A contains the original rights that are adjusted for the current modeled period based on APD records. Table 6.8-B summarizes the modeled APD for information on the original right not found as result of the water rights import operation. If this original right was actually modeled in the *LAR GeoDSS*, an error was introduced by allowing diversion of the full amount at the original location, plus the recorded alternate diversion. Details on the *LAR GeoDSS* APD modeling procedures are available in Appendix V – *Modeling Alternate Points of Diversion*.

Table 6.7 – LARV Modeled APD Links

A.

APD Demand Node	Water Right Holder (WD)ID
Bessemer_Ditch	(14) 527
Bessemer_Ditch	(14) 600
Bessemer_Ditch	(14)3528
Bessemer_Ditch	(14)3537
StCharles_Mesa	(14) 527
StCharles_Mesa	(14) 533
StCharles_Mesa	(14) 600
StCharles_Mesa	(14) 666
StCharles_Mesa	(14) 3537
PBWW_Northside	(14) 537
PBWW_Northside	(14) 573
Lamar_Canal	(67) 5041

B.

APD Demand Node	Water Right Holder (WD)ID
PBWW_Northside	(14) 501
PBWW_Southside	(14) 501
Fort_Lyon_Storage	(17) 553
Booth_Ditch	(14) 501
Booth_Ditch	(14) 591
PBWW_Southside	(14) 591
PBWW_Southside	(14) 535
PBWW_Southside	(14) 589
PBWW_Northside	(14) 591
BWW_Northside	(14) 590
BWW_Northside	(14) 535
Bessemer_Ditch	(14) 527

Table 6.8 – Original Rights Adjustment and Errors Based on Alternate Diversion Records

A.

Adjusted Link Name (original right)	APD Node Name
56_45_Fort_Lyon_Canal	Fort_Lyon_Storage
56_512_Booth_Ditch_4	PBWW_Southside
56_512_Booth_Ditch_8	PBWW_Southside
56_512_Booth_Ditch_4	PBWW_Northside
56_566_PBWW_Southside_3	PBWW_Northside

B.

Water Right not found	APD Node Name	Admin No
WARRANT BARNES & BAXTER	PBWW_Northside	4109
WARRANT BARNES & BAXTER	PBWW_Southside	4109
WARRANT BARNES & BAXTER	Booth_Ditch	4109
WEST PUEBLO DITCH	PBWW_Southside	8127
WEST PUEBLO DITCH	PBWW_Northside	8127

Storage Water Diversion and Exchanges

Flows through diversion structures in the basin can include water diverted from storage contracts and the winter water program, where calls for storage water are based on the user's natural flow entitlement, water needed, and available storage water. Currently, the *LAR GeoDSS* does not implement storage account modeling since the *LAR GeoDSS* lacks information on users' available storage water and the additional complexity of modeling individual storage accounts does not provide additional benefit to the comparative evaluation of improved management alternatives. The modeling of storage water in the system was based on diversion records, similar to the approach used in the APD algorithm as explained previously. The *LAR GeoDSS* implemented modeling of special high priority links to consider total storage water represented as a single link or individual account diversions as multiple links. These special links are created using a *LAR GeoDSS* tool accessed in the menu item *Arkansas Tools→Create Network Links from Diversion DB→Storage Links to Demands*. This tool searches the diversion database for entries indicating water coming from storage to create the corresponding modeling links. A complementary tool assigns the historical diverted amount from storage contracts to the links capacity time series. This tool is accessed from the menu item *Arkansas Tools→Populate Time Serie→Fix Capacity to Storage Links*. Table 6.9 shows a list of users for which storage links are modeled in the *LAR GeoDSS*; along with the total diversion from storage modeled from April 1999 to October 2001 for each user. Additional details on the storage water modeling tools are found in Appendix V – *Modeling Storage Water Diversion*.

Table 6.9 – *LAR GeoDSS*-Modeled Storage Water Summary

User Name	Total Storage Usage [Acre-ft]	User Name	Total Storage Usage [Acre-ft]
Amity_Canal	178541	Keesee_Ditch	8690
Animas_Town_Ditch	0	Kicking_Bird_Canal	0
Baldwin_Stubbs	0	Lamar_Canal	71217
Bessemer_Ditch	27527	Las_Animas_Consol	0
Buffalo_Canal	2473	Manvel_Canal	0
Catlin_Canal	28498	Otero_Canal	4627
Collier_Ditch	0	Oxford_F_Ditch	283
Colorado_Canal	464	PBWW_Northside	19278
Excelsior_Ditch	2315	Riverside_Diary	39
Fort_Bent_Canal	32585	Rocky Ford Ditch	0
Fort_Lyon_Canal	79083	Rocky_Fort_Highline	11163
Fort_Lyon_Storage	0	SissonStubbs_Ditch	0
Holbrook_Canal	50485	StCharles_Mesa	0
Hyde_Ditch	411	X-Y_Canal	0

Exchanges of natural flow for storage water are captured in this modeling methodology since there are records in the database of diversion from storage representing the exchange.

Additional releases from off-stream reservoirs for exchanges with the Arkansas River were modeled through the calibration structures when senior water rights were harmed due to the water exchange (e.g., Rocky Ford Ditch diversions affected by Holbrook Reservoir exchange with the Arkansas River).

Arkansas River Compact

The Arkansas River compact is an agreement between the states of Colorado and Kansas, signed in 1948, that ensures both states will receive their percentage share of the Arkansas River flow. John Martin Reservoir plays an important role in regulating flow in the Arkansas River for compliance with the compact. As a result of the 1980 operating plan, which was a resolution of the Arkansas River Compact Administration to provide more efficient utilization of storage water, reservoir inflows that are not immediately called are stored in separate storage accounts for Kansas and the ditches of Colorado Water District 67 according to rules specified in the resolution. The irrigation ditches of Colorado Water District 67 are located downstream of John Martin Reservoir. Water users can call for releases from their stored water independently according to their needs. The compact requires complex rules on storage and carry over water in the accounts. For this stage of the *LAR GeoDSS*, compliance with the Compact is achieved by guaranteeing historical deliveries to Kansas. These deliveries are based on available water in the Kansas account in John Martin, as accrued according to the compact rules. During the "what if" management alternative modeling, if water provided to the demand representing Kansas equaled or exceeded the historical flows then the simulation was assumed to be in compliance with the Compact. Since water entering John Martin Reservoir is subject to the storage rules imposed by the compact, implementing changes in historical amounts entering the reservoir require special attention. If flows entering the reservoir are reduced, there is a risk of not having enough water in the future to meet the compact requirements, however in this case the *LAR GeoDSS* will operate the system to provided the required data and replenish the historical level in the reservoir as soon as possible. In the case of larger flows entering the reservoir, unless the operational rules of the compact are modified, this water will be split in the storage accounts and will not be available for (1) replenish storage water used to meet water requirements in lower than historical flow periods, and (2) use additional generated water for water quality improvements by strategic releases. *LAR GeoDSS* simulations herein assume different degrees of flexibility in the Arkansas River compact operational rules.

Users in Colorado were treated differently in the management alternative simulations by assuming that these users participate in basin-wide programs to improve conditions in the basin. Therefore, diversions in Water District 67 were modeled as any other water use in the lower basin; i.e., these diversions are reduced from the historical diversions when considering scenarios for improving irrigation or reducing canal seepage. It was assumed that reductions from the historical diversion for these users are not a violation of the compact, and that the unused water can be used/stored by an implementation program. The priority assigned to the demand node for modeling Kansas flow requirements was set to 50, giving it a higher priority over other users in the system in order to secure compact compliance.

The Kansas water demand was represented at the USGS Coolidge, KS, gauging station (ARKCOOKS) located at the farthest downstream node of the Geo-MODSIM network. A special structure was implemented in the *LAR GeoDSS* to handle additional flows to Kansas during the modeling of the management alternatives. This structure creates a System Sink node (named "__SYSTEM_SINK"), which has a low priority (i.e., 2200 in simulation and 4850 in calibration) and a high demand node linked to the node ARKCOOKS (Figure 6.8). The structure is automatically added to the Geo-MODSIM network at run time. Flow to the system sink was added to the flow to the ARKCOOKS station to represent the total flow to Kansas in the *LAR GeoDSS* simulations.

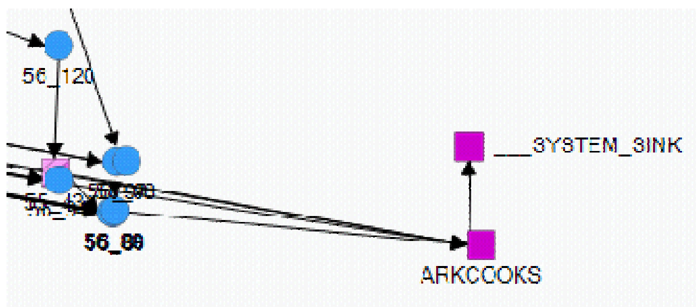

Figure 6.8 – System Sink in the *LAR GeoDSS* network

Canals Interfaces

The concept of a *terminal interface* was implemented for modeling the canals in order to allow water to flow downstream of the diversion demand node to be captured at a terminal *flow-through* demand node that can implement a fractional return to the river system. *Terminal interfaces* are nodes located at the ends of the canals through which return flows can occur. Special terminal interfaces, r*eservoir interfaces*, are implemented when the canal flows into a reservoir. *Reservoir interfaces* allow a fraction of the water in the canal to be stored in the reservoir or a specified time series of flows to be stored. The interfaces were implemented in the data-model non-storage feature class using the *ARK_Type* field. Nodes in this interface were assigned with *ARK_Type* = 'Terminal Interface' and

ARK_Type = 'Reservoir Interface', depending on the type of interface. Both interface types handle a return flow fraction as specified in the data-model *ARK_Return* field. At run time, the *LAR GeoDSS* converts the interface nodes and the diversion demands to *flow-through* demand type nodes. In addition, the *LAR GeoDSS* sets the *flow-through* demand node parameters accordingly, where diversion demands are assigned with a return fraction of 1 and interfaces are set with the data-model specified fraction. Though the return fraction could be estimated for canals with available measured returns, the current *LAR GeoDSS* uses the calibration structures to account for canal returns.

Carrier Diversion Structure

Some diversions act as carriers of water for other users, usually for storage purposes. These diversion points are marked in the diversion database with the field *T*=3. A Carrier Diversion Structure is implemented in the Geo-MODSIM network to allow diverting water for downstream demand nodes. The structure consists of a *bypass credit link* that connects the downstream and upstream nodes of demand nodes representing diversions (Figure 6.9). The flow through the *bypass credit link* is considered as part of the diversion flow (i.e., surface water delivered to the demand node). This link is assigned with zero cost allowing downstream demands on the canal (e.g., *reservoir interfaces*) to call for water through the bypass link.

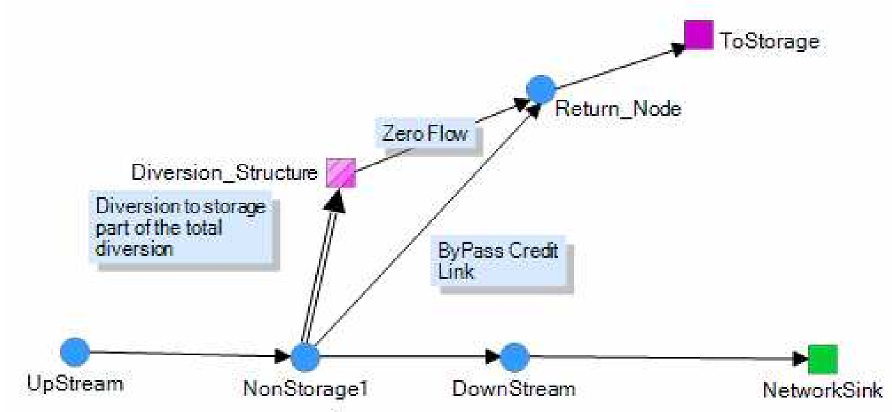

Figure 6.9 – Carrier diversion structure diagram

The carrier link is named using the name of the diversion demand node, followed by "_CarrierByPass_" and the ID of the user for which the water is carried. A summary of the diversion structure IDs that have entries with T=3 in the database is shown in Table 6.10.

Table 6.10 – Carrier Structures Summary (based on diversion records)

WD	ID	Name	Carried For ID
14	533	BESSEMER DITCH (Municipal use in the St. Charles mesa water district)	527
14	540	COLORADO CANAL (Single Entry)	3537
17	648	FORT LYON STORAGE CANAL	3525
67	614	LAMAR CANAL	3512
14	539	EXCELSIOR DITCH	3537

The Fort Lyon Canal requires a manual entry in the diversion database to represent the Kicking Bird Canal diversion, which takes water through the Fort Lyon Canal diversion. Even though there are diversion records for the Kicking Bird Canal, no records are found in the database indicating that Fort Lyon Canal as the carrier. An entry is manually added to the diversions table to define this physical phenomenon for the *LAR GeoDSS* interpreter, but no data are needed for this entry (Table 6.11). An inconsistency could have been introduced by this measure if the Kicking Bird Canal diversions were not added to the database for total diversion at the structure since water passing through the bypass link is added to the diverted water.

Table 6.11 – Manual Diversion Database Entry for Fort Lyon to Create Water Carrier Structure

WD	ID	T	F	Name
17	553	3	555	FORT LYON CANAL

In this implementation, any water that flows through the diversion structure is used to supply the water demand. The structure guarantees supply to demands downstream of the diversion nodes, but lacks specification of ownership of the diverted water. This situation only appears in the case of Fort Lyon Canal diversion modeling where the Kicking Bird Canal uses the bypass link to convey only water in excess of the Fort Lyon diversion, using the Fort Lyon Canal diversion as supply.

Canal Seepage Modeling

Canal seepage field studies conducted in the Arkansas River Valley indicate significant seepage losses (Gates et al. 2006). Studies conducted in the regions both upstream and downstream of John Martin Reservoir show seepage losses ranging from 0.003 m^3/s per km (0.2 ft^3/s per mile) to 0.065 m^3/s per km (3.7 ft^3/s per mile). There is a high variability in the losses depending on the underlying soil types, water levels in the canals, adjacent ground water levels, and other factors. Canal seepage was modeled in the baseline using the user defined coefficient ($\bar{s}$), which computes seepage loss as a fraction of the diversion, where the calculated seepage is assumed to occur uniformly along the full length of the canal. As a first approximation to the overall system seepage, the *LAR GeoDSS* assumed a baseline seepage loss coefficient $\bar{s} = 0.2$ for all canals in the Valley based on the regional groundwater model average conveyance efficiency (E_C) (Gates et al. 2002).

Future refinements should adjust the coefficient based on detailed field studies and updated groundwater modeling results.

Stream-Aquifer Interaction Predictions in the Geo-MODSIM Network

Stream-aquifer interaction predictions were assumed to be an average result of the interaction as evenly distributed over the grouping area. Nodes in the data-model that intersect the grouping area are assigned to a corresponding return flow (or depletion) using a special construct. At the beginning of the simulations, the ANN module builds a *source-sink* structure with links in and out of all nodes flagged for conjunctive use modeling. The structure used the connecting link upper bounds combined with a large negative cost to model the predicted ANN returns/depletions. Figure 6.10 illustrates the source/sink MODSIM structure to provide calculated return flows to the stream network and depletions from the network.

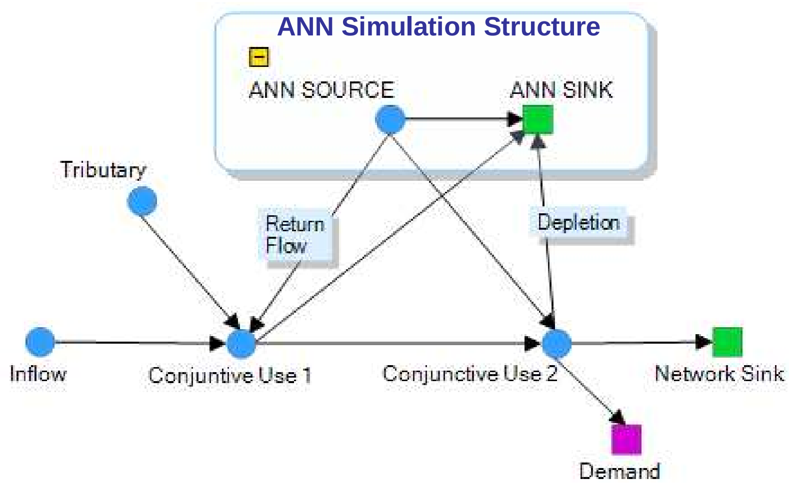

Figure 6.10 – ANN module MODSIM simulation structure

The ANN module was coupled with the MODSIM model to perform dynamic stream-aquifer interaction. The ANN module is initialized after MODSIM is initialized and the

ANN explanatory variables are calculated along with the MODSIM solution (each time step and iteration, if specified). Figure 5.1 shows a simplified diagram of the ANN module and MODSIM coupling. Detailed ANN-MODSIM coupling at run time is explained in Appendix III – *ANN predictions in Geo-MODSIM*.

Based on the ANN development results, the expected performance of the two sets of trained ANNs can be compared for the different reservoir operation scenarios. The *LAR GeoDSS* simulation was implemented with the *Dataset_A* ANNs (*AllScen_GWR_v8BArk_b* and *All_Scen_GWR_v8BTrib_c*). These ANNs have the more parsimonious structure of the two sets with less number of recurrent explanatory variables (see discussion on Chapter 4 – *The Simulation Challenge*).

Reservoir Salt Transport Model

The ANN module predicts concentrations at the John Martin Reservoir outlet based on reservoir inflow characteristics and initial and ending volumes (See Chapter 4). Since the flows and concentration explanatory variables are dynamically linked with the simulated values, the explanatory variables may diverge from the training values depending on the type of run and the reservoir operating rules. This module implements an option where the measured concentrations are used to build the ANN simulation dataset, which is recommended for ANN testing only. Improvement alternatives analysis uses the modeled concentrations for the reservoir salt transport allowing prediction of changes in the baseline transport based on the changes in the modeled explanatory variables.

The WQM was enhanced to integrate the ANN-based reservoir salt transport. If the reservoir salt transport model is active, the WQM overwrites the calculated concentrations at the reservoir outlet with the ANN predicted concentrations. Links immediately downstream of the reservoir outlet are assigned with the predicted concentrations. This type of transport modeling is expected to create an imbalance in the mass conservation at the node representing the reservoir outlet.

Simulation Scenario Manager

The custom *LAR GeoDSS Simulation Scenario Manager* implements the following management alternatives: (1) areal aquifer recharge reduction fraction per command area, (2) canal seepage reduction by canal system, (3) sub-surface drainage improvements per grouping area, and (4) vertical drainage pumping per grouping area. The Simulation Scenario Manager stores the management alternative preferences in the geo-database, where each alternative also contains information about the location of the groundwater modeling (MODFLOW-MT3DMS) output files and trained ANN export files. Figure 6.11 shows two sample views of the Simulation Scenarios Manager user dialog. The active scenario is selected using the combo-box list at the top, with several buttons to create, save and delete simulation scenarios. The lower portion of Figure 6.11-A displays the table for setting the drainage intensity and pumping increase percentage per grouping area. Figure 6.11-B shows the management alternative preferences for aquifer recharge reduction and canal seepage reduction per canal command area. Additional options include start and end dates of the irrigation activity (for aquifer recharge). Figure 6.11-C shows an area of the Simulation Scenario Manager displaying flags and preferences for the *LAR GeoDSS* project such as: (1) global irrigation activity deep percolation fraction, (2) active modules (water quality and ANN), (3) reservoir transport model status, (4) run type, and (5) calibration preferences (calibration network name).

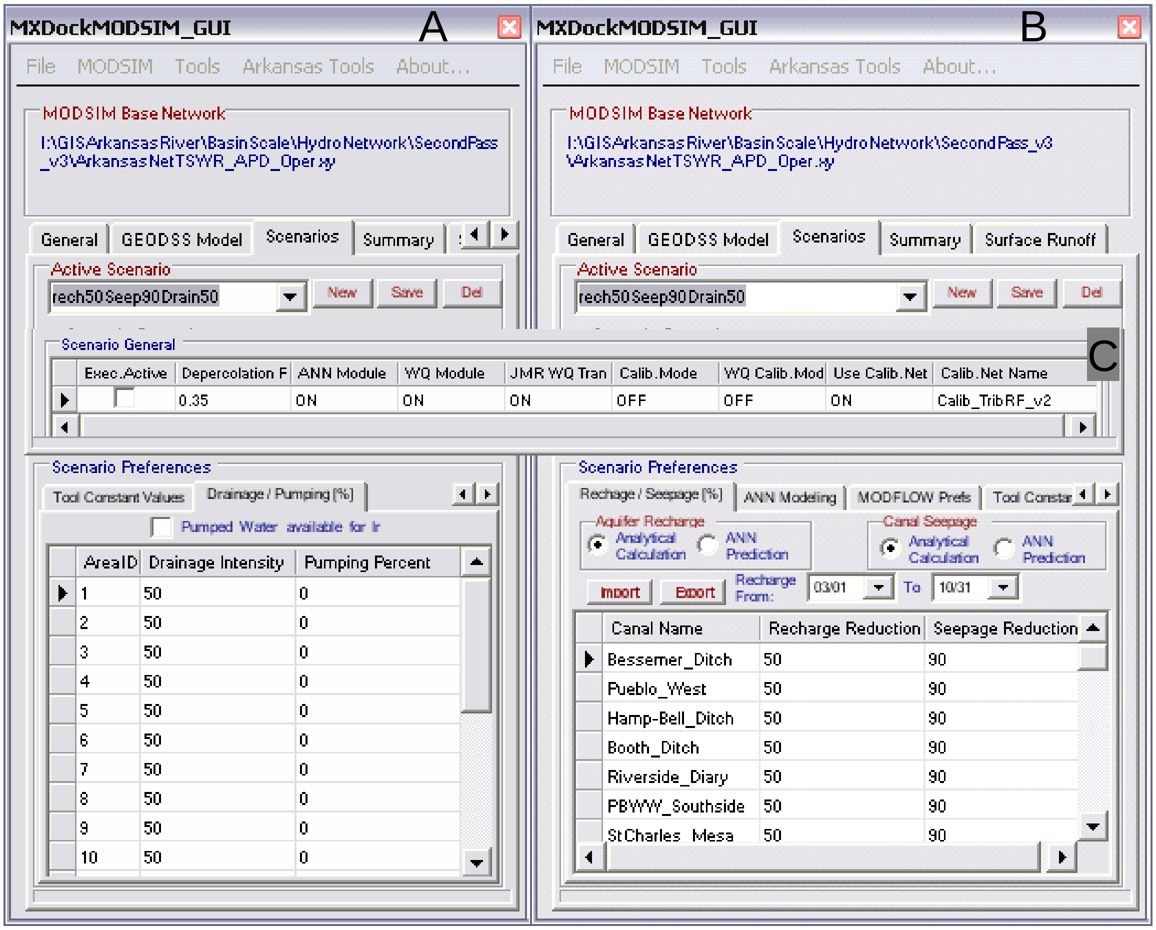

Figure 6.11 – Simulation Scenario Manager User Dialog Sample (*LAR GeoDSS*)

Figure 6.12 shows user dialog views for the management alternative-based ANN, MODFLOW-MT3DMS preferences. In Figure 6.12-A, the user specifies the ANN export file locations and names for the stream-aquifer interaction (both main river and tributaries). The user enters (Figure 6.12-B) location and name of the MODFLOW project (*.*mfs*), the MODFLOW river cells file (*.*riv*), and the MT3DMS output (*.*con*) files associated with each management alternative.

A tool to assist users in setting management alternative preferences for all canal command areas or all grouping areas is also available in the Simulation Scenario Manager (Figure 6.13).

Simulation Scenario Analysis Tool

This section describes a set of custom tools implemented for the *LAR GeoDSS* to expedite results processing and analysis. The tools assist in checking, analyzing and comparing basin-wide simulations results. The summary tools are accessed at the "Summary" tab in the *LAR GeoDSS* interface.

The first tool summarizes each run individually by providing four tables containing the system-wide summary of network inflows, MODSIM calculated channel losses, water demand, water shortages, measured flow with shortages (for calibration control) and flow checks on high priority links. The high priority links, i.e., the storage contracts and APD modeling links, are checked to corroborate that they are flowing at maximum capacity at all times, as expected in the algorithm. The check summary table includes links flowing at partial capacity at any point of the simulation. The network calibration structures were designed to provide any additional water for satisfying all demands and therefore no shortages are expected at any time. The water shortage summary is valuable since it identifies total water shortages in the system per time step, as well as detailed locations of the shortages for a particular time step. Figure 6.14 shows a sample of the summary tables generated in the *LAR GeoDSS* interface (Summary Tab).

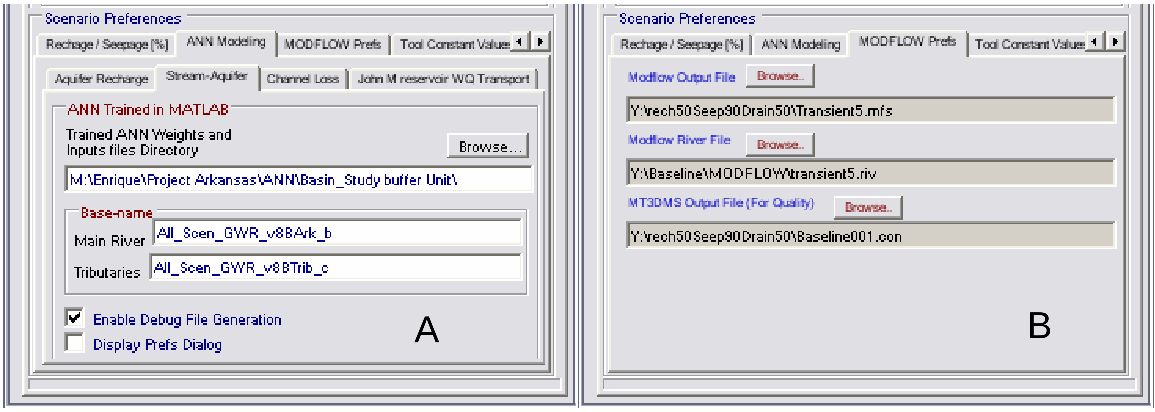

Figure 6.12 – Simulation Scenario Manager ANN and groundwater modeling preferences sample

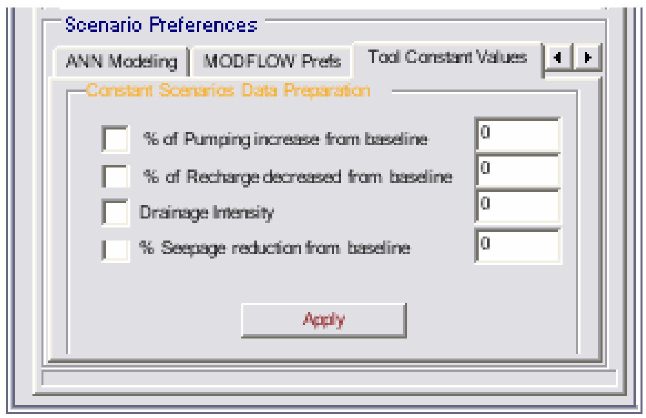

Figure 6.13 – Simulation Scenario Manager batch preferences setting tool

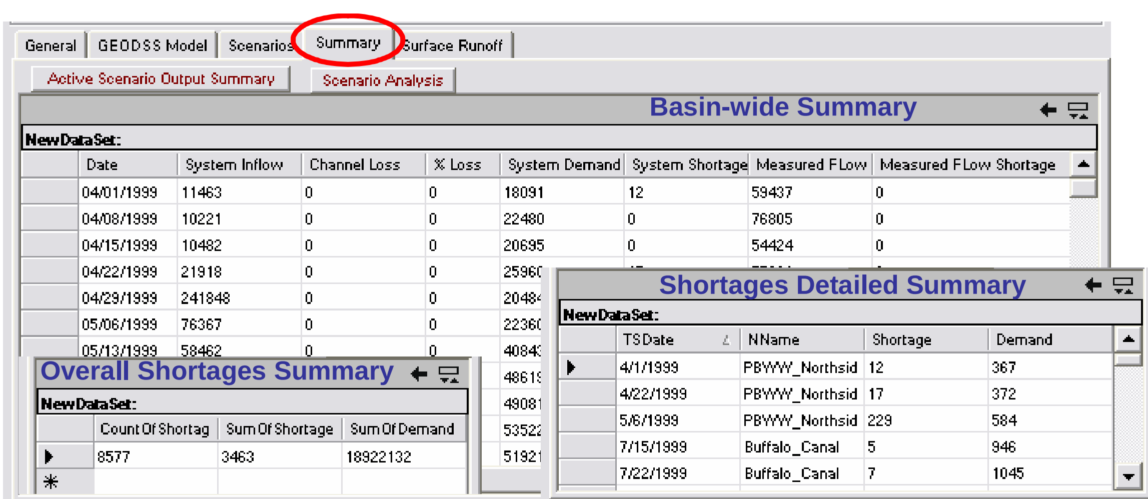

Figure 6.14 – Single run performance summaries in *LAR GeoDSS*

The second tool compares the system-wide baseline performance with the results from alternative management scenarios. Comparison is based on (1) reservoir storage in Pueblo and John Martin Reservoirs, (2) flows and concentration summaries at key points in the basin, (3) Arkansas River compact compliance, (4) stream-aquifer interaction modeling summary, and (5) calibration flows summary. Figure 6.15 shows the simulation scenarios comparison interface as displayed in ArcMap. The interface consists of four areas: Area 1 allows selection of the available simulation scenario to include in the analysis and selection of the baseline simulation; Area 2 displays Pueblo and John Martin Reservoir storage plots (only Pueblo Reservoir is shown in Figure 6.15); Area 3 provides a tabular summary of total water in storage at the end of the simulation, total diversions, diversion shortages, diversion average concentrations, canal seepage (as calculated by the simulation scenario manager), total flow and average flow concentrations to Kansas, total return flow/depletions and corresponding average concentrations (as grouped according to main river and tributaries), total calibration flows (i.e., inflows and outflows), and John Martin Reservoir salinity transport indicators (i.e., total mass inflows/outflows and the corresponding ratios). Area 4 in Figure 6.16 provides comparative plots of basin-wide total diversions, shortages, seepage losses, return flows, river depletions, Arkansas River compact flows to Kansas and average concentrations for each time step.

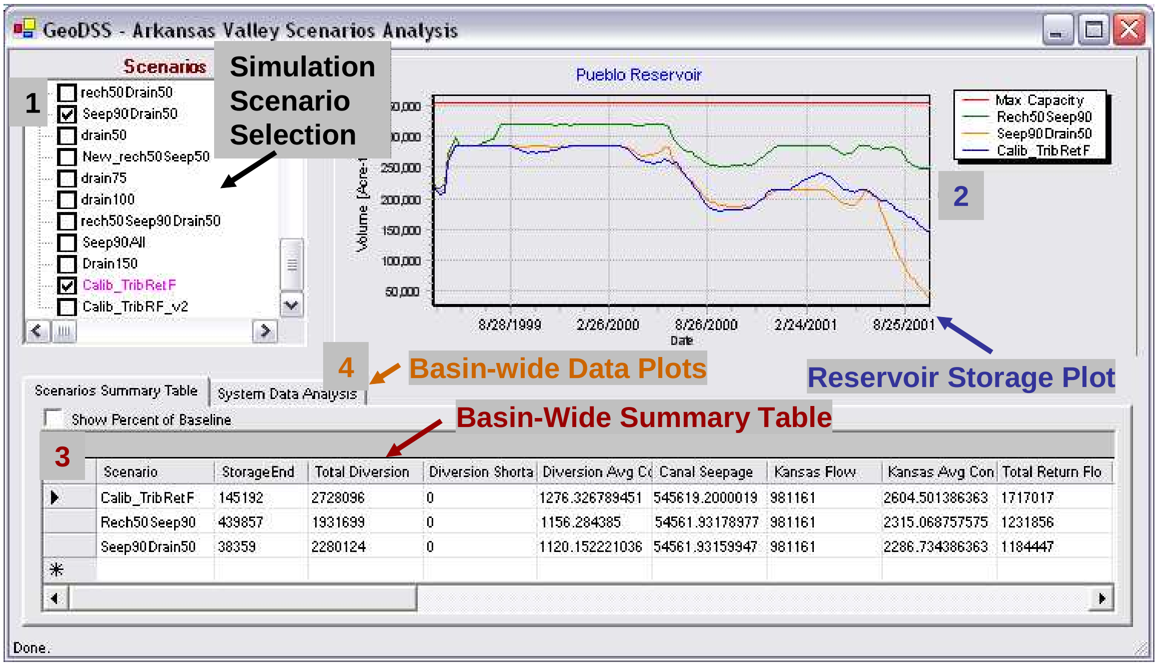

Figure 6.15 – Interface of the simulation scenarios comparison tool in ArcMap

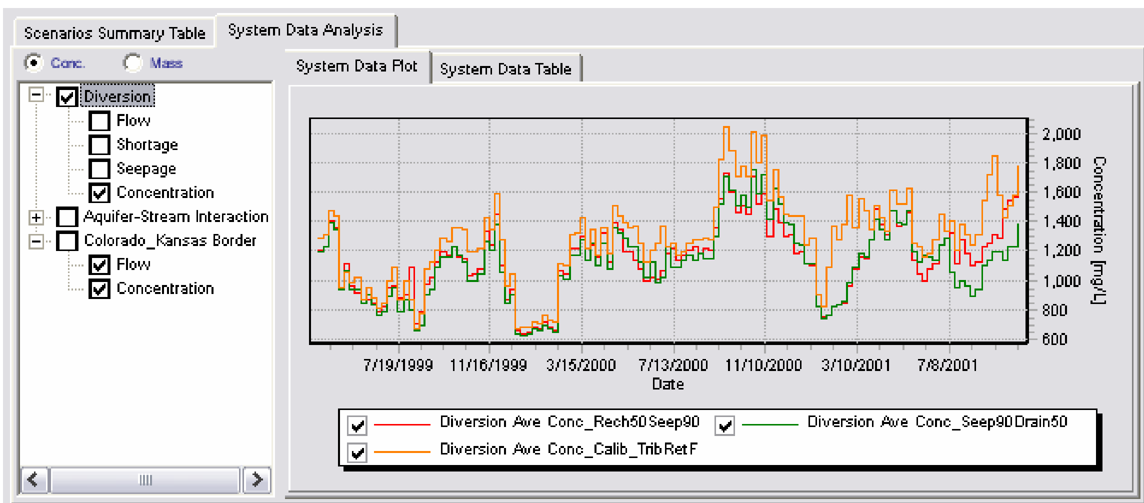

Figure 6.16 – System-wide result summary plots interface

Model Calibration

A weekly time step was selected for this case study, providing a compromise between accurate water rights modeling and adequate representation of the system for planning purposes. Although errors could be introduced in the allocation of water by not accounting for the daily variability, weekly time steps provide reliable modeling of the system yield. The *LAR GeoDSS* Base-Network was populated with weekly historical flows from April 1999 to October 2001 extending over the same period as the available regional-scale groundwater model. The baseline modeling system enabled the ANN-based stream-aquifer interaction modeling methodology and the WQM includes the John Martin Reservoir salt transport model as presented in Chapter 4. This modeling system was calibrated for both water quantity and quality using the *LAR GeoDSS* hydrologic calibration tools and procedures introduced in Chapter 5. Calibration structures were created to provide local gains and losses, and unmeasured concentrations for inflows were adjusted to match as closely as possible the measured concentrations at the control points. The calibration network used the historical volumes in the reservoirs as storage targets for computing calibration flows that resulted in replication of the historical reservoir storage levels.

Modeling Underlying Characteristics

Since a weekly time step was selected for network flow simulation, it is assumed that flow routing can be neglected in the network stream and canal reaches. This means that changes in storage in the connecting elements of the model representing streams and canals are neglected in this modeling system, i.e., the flow entering a link is equal to the flow leaving the link. At the nodes, complete mixing was assumed for water quality modeling; therefore, the concentration of flows leaving the node are assumed to have concentrations equal to the total mass entering the node divided by the total volume flowing into the node during the given time step.

Although potentially large errors could exist in the flow measurements, one of the main assumptions in the model calibration was that the surface water measurements are accurate.

Local gains and losses were calculated based on the measured surface water flows with the ANN predicted stream-aquifer interaction considered as known input/output to the system and gains and losses calculated accordingly to alleviate any discrepancy with the measured flows.

With specification of a weekly time step, the travel time of water through the flow networks was assumed to be less than one week, i.e., water travels from any point in the system to another within the time step interval. Travel times are a function of stream and river reach conditions. Based on the average-flows and a representative rate of travel from Pueblo Reservoir to John Martin Reservoir as given by Livingston (1978), one week is approximately the time that would take an average-flow release from Pueblo Reservoir to reach the state line (approximately 185 (miles) downstream at 0.9 (h/mi)).

Some additional assumptions in the Arkansas River basin modeling: (1) no diversion data were assigned to the Pueblo Board of Water Works Southside intake diversion, since diversions at this point in the system are apparently linked to the Riverside Dairy (id = 536); (2) Booth Ditch was not modeled since no records of diversion exist after 1973. Stream-aquifer interaction was neglected in the tributaries or portions of the Arkansas River outside of the groundwater modeling grouping areas, or for those portions of the tributaries outside of the irrigated valley. Aquifer-stream interaction was not considered for: (1) Purgatoire River, (2) Chico Creek, (3) Fountain Creek, (4) Two Butte Creek and (5) the Arkansas River upstream of the ARKMOFCO station. In the Purgatoire River, the portion of the stream that would be modeled is surrounded by irrigated fields and is located in a groundwater modeling grouping area covered for the most part by John Martin

Reservoir. In this case, the ANN explanatory variables lose their meaning. The location of the PURLASCO gauging station provides baseline flows that include groundwater return flow close to the reservoir inlet, thereby reducing the effect of this modeling restriction. For the water quality modeling, it was assumed that the flow-concentration relationships developed for stations with sporadic data adequately represent the concentrations of the average weekly flows. The values computed at the station are used in the modeling regardless of the measurement availability.

Calibration Results and Analysis

Since the calibration network was set up to meet all historical flows in both demands and control points (gauging stations), water shortages occurring during calibration required careful analysis. The *LAR GeoDSS* simulation analysis tool was used to check for water shortages. Table 6.12 shows the summary of water shortages amounts during a calibration run. In this case, water shortages for the three nodes were caused by missing or misinterpreted water rights, exchanges or ADP at these points that generated these errors.

Table 6.12 – Calibration Water Shortage Summary

NName	SumOfShortage
Buffalo_Canal	144
Excelsior_Ditch	12
PBWW_Northside	3307

With the exception of minor round-off errors, the flow checks at high priority links confirmed that the storage water contracts and APD adequately model these components, thereby leaving the available natural flow rights to satisfy the remaining water demands in the system.

During calibration, both Pueblo and John Martin Reservoirs operate at the defined storage targets (Figure 6.17 and Figure 6.18).

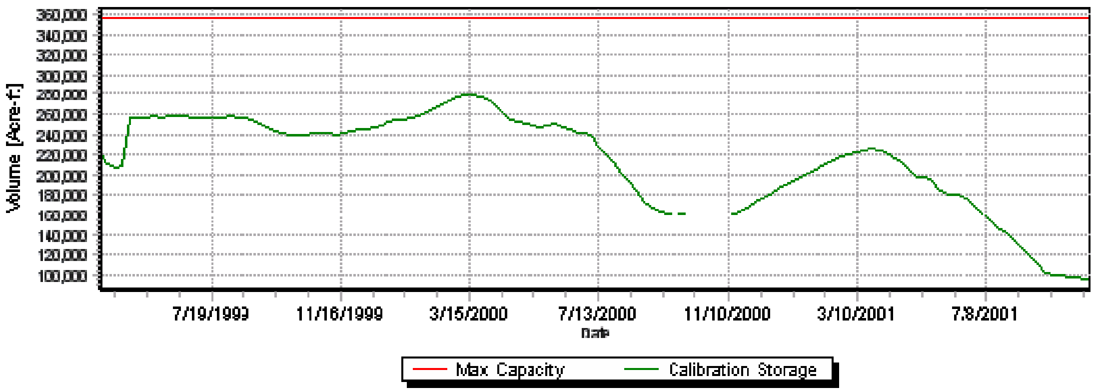

Figure 6.17 – Pueblo Reservoir storage content calibration run

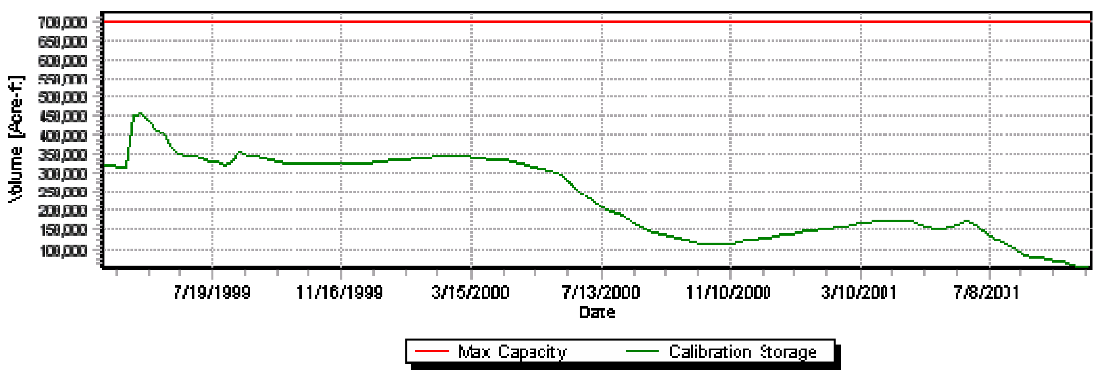

Figure 6.18 – John Martin Reservoir storage content calibration run

Since all control points in the system, i.e., gauging stations, exactly met the measured flows; each of these nodes (*flow-through* demands) provided the downstream reach with exactly the measured flow each time step.

Analysis of the calibration network results pointed to problems with the diversion records for Water District 14 and 17. Gains and losses larger than expected in the reach led to identification of missing inflow or outflow data. From this analysis, it was concluded that diversion records for the structures with double WDs (Table 6.3) are split between the districts for water year 1999, whereas the storage diversion records seem to be duplicated during the same period. Rules to implement these findings were coded into the *LAR GeoDSS* data import tools.

Calibration Results per River Reach

The calibration analysis was carried out using the control points for the surface drainage areas. ArcHydro tools were used to construct the surface drainage areas for the control points in LARV and these drainage areas were used to group the system nodes by calibration reach for analysis of gains and losses. The calibration reach was named after its downstream station. Figure 6.19 shows the control point surface drainage areas used for grouping nodes in the calibration analysis.

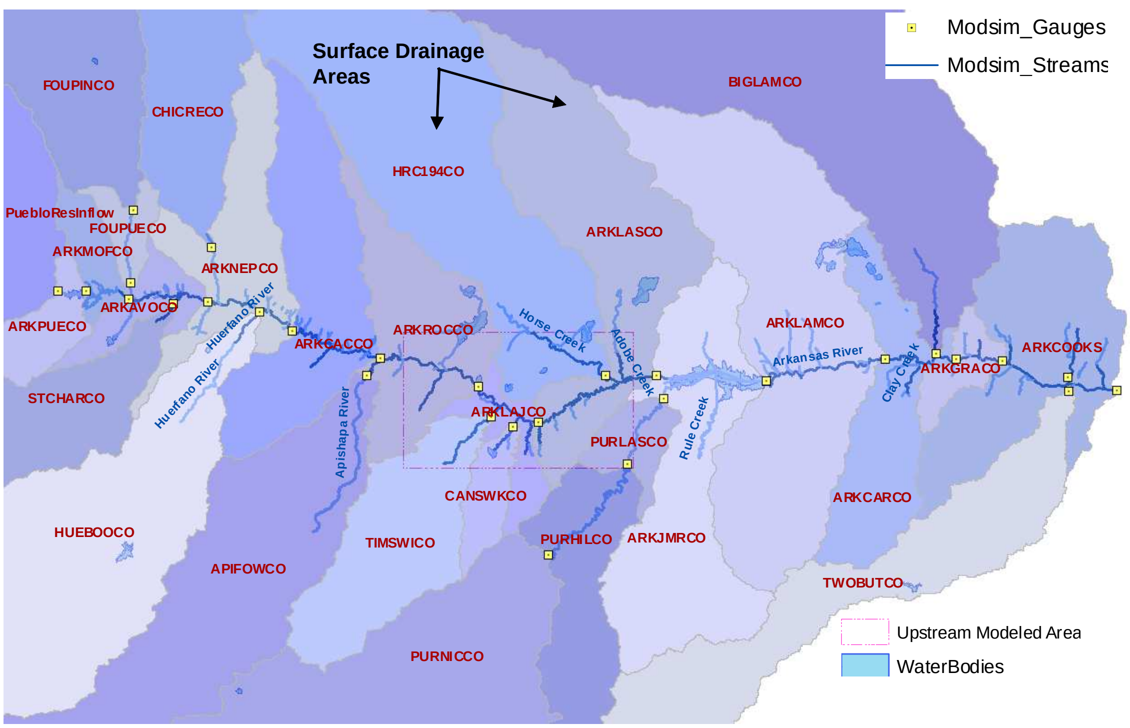

Figure 6.19 – Control points surface drainage areas

The system inflows and outflows were analyzed per calibration reach, representing water handled by the calibration structures to match measured flows at the control points. Figure 6.20 and Table 6.13 present a summary of total inflows and outflows during the simulation period for reaches marked as system sources, i.e., reaches corresponding to the most upstream gauging stations. Inflows to Pueblo Reservoir were not included in the summary plot since this was a calculated inflow, modeled using the upstream source link of the ARKPUECO intermediate reach. Total inflow is on the order of 1.3 million of acre-ft during the simulated period. The summary shows that the largest tributary inflow to the Arkansas River occurs at Fountain Creek (FOUPINCO reach). Excess water in source reaches occurs when the ANN-predicted return flows upstream of the gauging station are larger than the measured flows. As a result of the calibration procedure, the source nodes release flows that exactly match the downstream measured amounts. System source reaches with modeled stream-aquifer interaction include: APIFOWCO, BIGLAMCO, CANSWKCO, HRC194CO, HUEBOOCO, STCHARCO, TIMSWCO, and WILDHOCO.

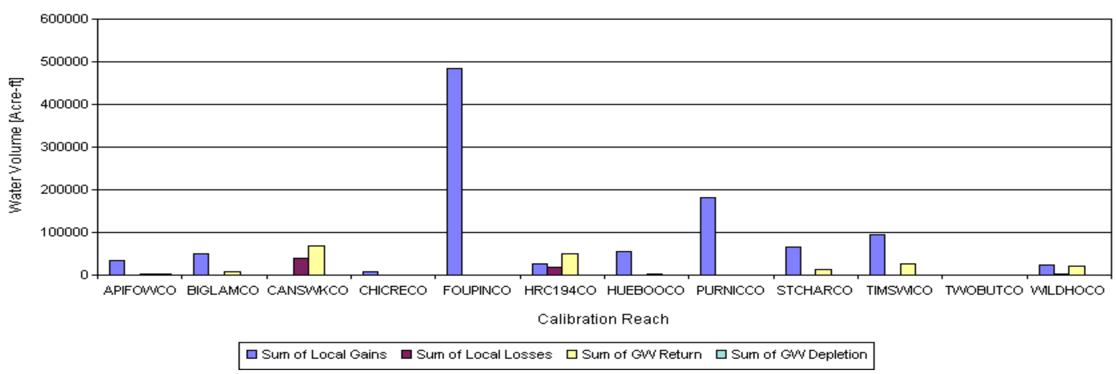

Figure 6.20 – Measured system inflows and outflows at the system source reaches

Table 6.13 – Summary Calibration System Sources Inflows/Outflows

Reach	Inflows [Acre-ft]	Losses [Acre-ft]	GW Return Flow [Acre-ft]	River Depletion [Acre-ft]
APIFOWCO	33356	6	3365	3914
BIGLAMCO	50346	0	8073	783
CANSWKCO	214	39965	69040	0
CHICRECO	6961	0	0	0
FOUPINCO	482964	0	0	0
HRC194CO	26227	17995	49101	1315
HUEBOOCO	55925	369	3143	1126
PURNICCO	181259	0	0	0
STCHARCO	67104	1142	12560	619
TIMSWICO	94531	0	27616	0
TWOBUTCO	290	0	0	0
WILDHOCO	24612	3741	20190	26

The system local gains and losses were totaled per calibration reach, where the gains were located at the upstream ends of the reach and the losses were located at the downstream station. Figure 6.21 and Table 6.14 shows the calibrated system gains and losses per calibration reach. Stations showing gains and losses simultaneously in the summary indicate that, over time, the reach switches between gaining and losing conditions. An example of this gain and loss behavior during the simulated period is shown in Figure 6.22 (reach ARKLAJCO). In this example, predominant gaining and losing conditions appear to occur in consecutive time steps, and rarely occur simultaneously. Although, the calibration structure avoids unnecessary addition and removal of calibration water, the locations of the water demands and reach inflows might require additional water upstream, while at the same time removing water downstream. Detailed gain and loss summary plots for all the control points are given in Appendix V. The reach ARKPUECO shows local gains corresponding to the Pueblo Reservoir inflows since the upstream source node (*PuebloResInflow*) is not provided with measured inflows; i.e., inflows are auto-calculated to match the reservoir operation, reach diversions and measured flow at the downstream station.

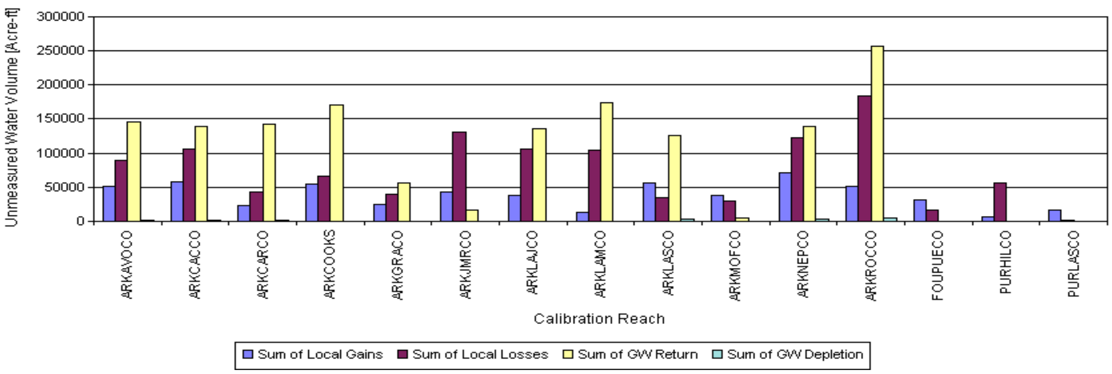

Figure 6.21 – Calibrated system gains and losses

Table 6.14 – Summary Calibration River Reach Gains and Losses

Reach	Inflows [Acre-ft]	Losses [Acre-ft]	GW Return Flow [Acre-ft]	River Depletion [Acre-ff]
ARKAVOCO	51008	88889	146561	1857
ARKCACCO	57871	106697	138753	2359
ARKCARCO	23561	43767	142386	2349
ARKCOOKS	55004	66578	171483	209
ARKGRACO	24283	39655	55579	0
ARKJMRCO	42493	130123	17331	144
ARKLAJCO	37362	106691	136002	270
ARKLAMCO	13753	104441	174324	0
ARKLASCO	55859	34560	126476	3461
ARKMOFCO	37929	29769	5561	0
ARKNEPCO	71190	123271	138644	3012
ARKPUECO	1366378	0	0	0
ARKROCCO	51770	184051	257563	4489
FOUPUECO	30786	16126	0	0
PURHILCO	5880	56176	0	0
PURLASCO	17335	1174	0	0

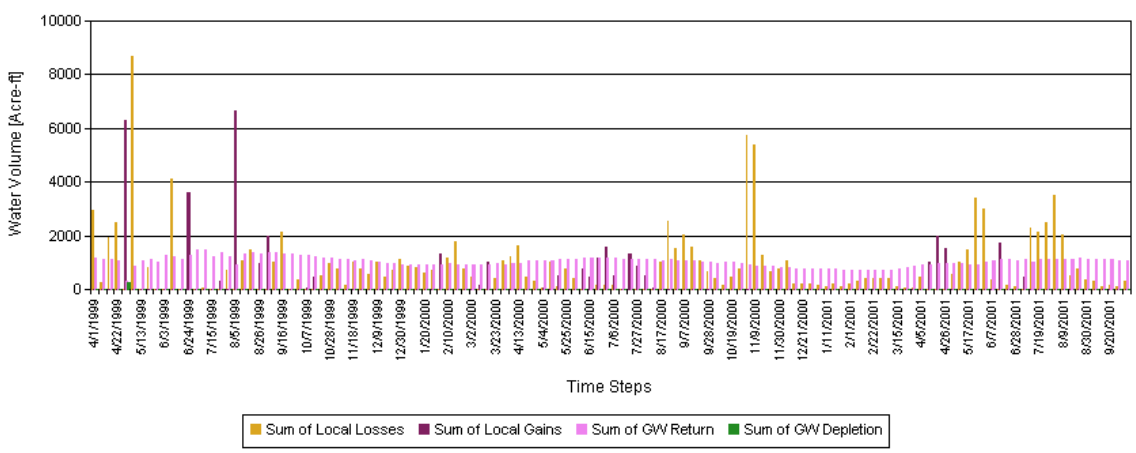

Figure 6.22 – Local gains and losses during calibration for reach ARKLAJCO

Stream-Aquifer Interaction Modeling Analysis

In this section, the ANN predicted aquifer return/river depletions were analyzed using the *LAR GeoDSS* calibration tools. Stream-aquifer interaction was processed using Geo-MODFLOW to evaluate performance of the trained ANN in the *LAR GeoDSS* based on: (1) the quality of the predictions with unknown initial conditions and (2) the effect of using imperfect previous time step explanatory variables; i.e., using previous time step predictions as explanatory variables rather than the "perfect" modeled values. For the former, the ANN module priming procedure (described in Chapter 3) was tested for providing the ANN with reasonable initial conditions for the modeling. The ANN stream-aquifer interaction prediction was analyzed using two different grouping elements: (1) the stream-aquifer modeling grouping areas and (2) the calibration reaches. The first grouping provides direct comparisons with the MODFLOW-MT3DMS modeling, whereas the second allows comparison of the predictions against the measured gains and losses.

Geo-MODFLOW and ANN Predictions

The ANN was trained to represent return flows and salt loadings for the grouping areas, assuming they were evenly distributed within the grouping area nodes. Therefore, a weak correlation is expected when comparing the ANN results with the MODFLOW modeled values at a higher resolution than the grouping areas; e.g., comparing individual MODSIM nodes and the corresponding upstream link MODFLOW return flows. Earlier experimentation using predictions of flows/loadings per unit length in the grouping areas showed little improvement in matching MODFLOW modeled return flows. However, this approach proportionally distributes return flows and salt loadings among short and extremely large segments.

ANN modeling grouping areas-based Analysis

The *LAR GeoDSS* stream-aquifer interaction modeling was analyzed by aggregating the predictions and MODFLOW-MT3DMS modeled values for the interaction modeling grouping areas (Figure 4.2). Geo-MODFLOW summarized the modeled interaction per grouping area to be compared with the *LAR GeoDSS* values. The net aquifer return flow with negative sign represents a MODFLOW's aquifer output; for comparison, *LAR GeoDSS* was plotted to match the MODFLOW sign. The results were analyzed separately for the Arkansas River and tributaries.

Arkansas River Stream-Aquifer Interaction

The mean squares error (MSE) quantifies the amount by which an estimator differs from the true value of the quantity being estimated. MSE is computed as the expected value of the squared difference between the observed and predicted values (Lehmann and Casella 1998). The root mean squared error (RMSE) is computed as the square root of the MSE, being for unbiased estimators the standard error in the same units of the quantity being estimated. Figure 6.23 shows a comparison of the MODFLOW-MT3DMS and *LAR GeoDSS* total net return flow estimated for the five modeled grouping areas in the Arkansas River, including the MSE and RMSE for each region. The overall average expected root mean error = 10.68 acre-ft/km. The predictions improved after the first modeled year, where Figure 6.24 shows that larger errors occurred in the first year of the simulation. The average RMSE over the second and third years = 6.84 acre-ft/km.

The average predicted concentration of return flows to the Arkansas River over the modeled period was compared with the MODFLOW-MT3DMS modeled concentrations (Figure 6.25). Except for grouping area 11, there was a slight tendency to under estimate the concentrations. Figure 6.26 shows the concentration RMSE per grouping area and per year, with the overall average RMSE = 200 mg/L. Similar to the flow prediction performance, the largest errors occurred during the first year with respect to the MODFLOW-MT3DMS modeled concentrations, with the average RMSE over years 2000 and 2001 = 132.82 mg/L.

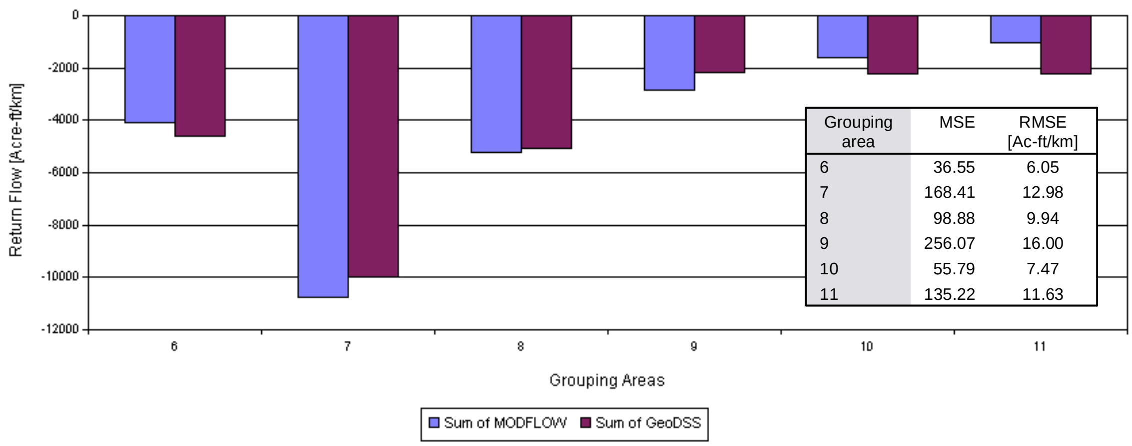

Figure 6.23 – Arkansas River total net return flow comparison for the modeled grouping areas

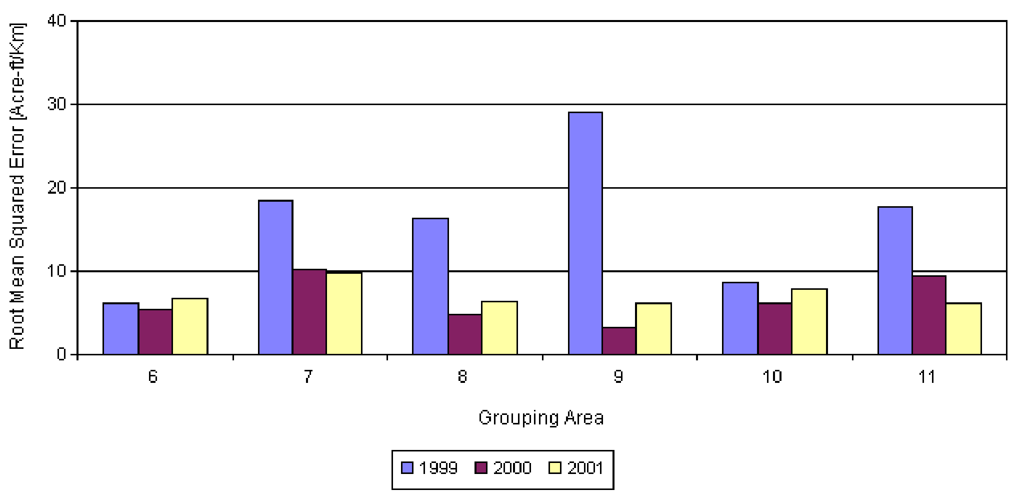

Figure 6.24 – Aquifer return flow RMSE per year per grouping area

Both the *LAR GeoDSS* net returned volume and concentration results show agreement with the corresponding MODFLOW-MT3DMS modeled values in the grouping areas. The year 1999 exhibits the largest errors, resulting in considerable degradation of the overall prediction performance.

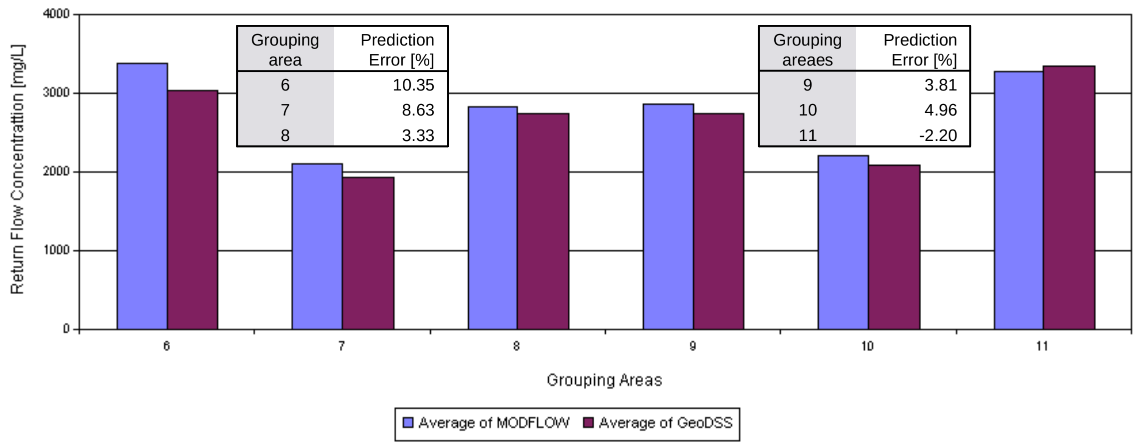

Figure 6.25 – Arkansas River Average concentration comparison for modeling grouping areas

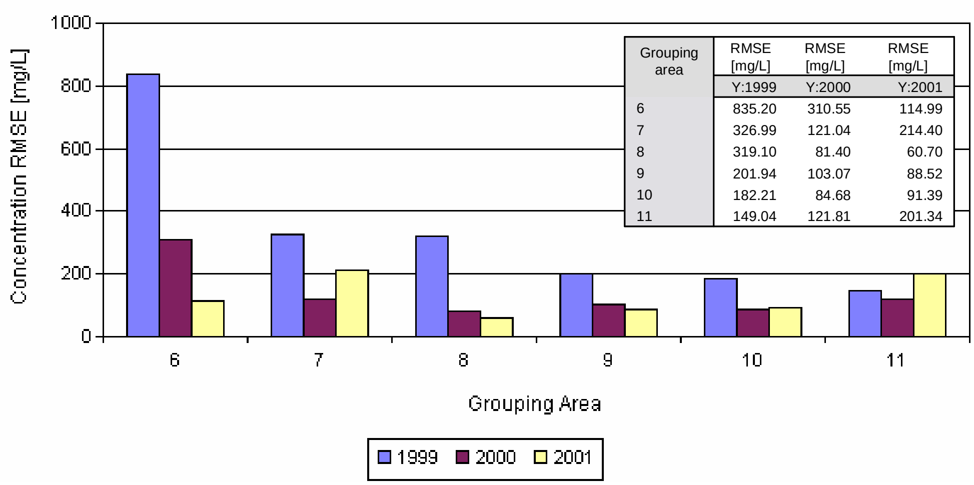

Figure 6.26 – Arkansas River Concentration RMSE per grouping area per year

The basin-wide stream-aquifer modeling results are summarized in Figure 6.27. The total basin-wide return flow predictions seem reasonable based on the range of the total modeled grouping area predictions. Slightly larger return flows were predicted in the upper half of the grouping areas, where the average net return flows for grouping areas 1 to 10 = 1634.51 acre-ft/km, as compared with the average net return flows for grouping areas 11 to 20 = 1357.80 acre-ft/km.

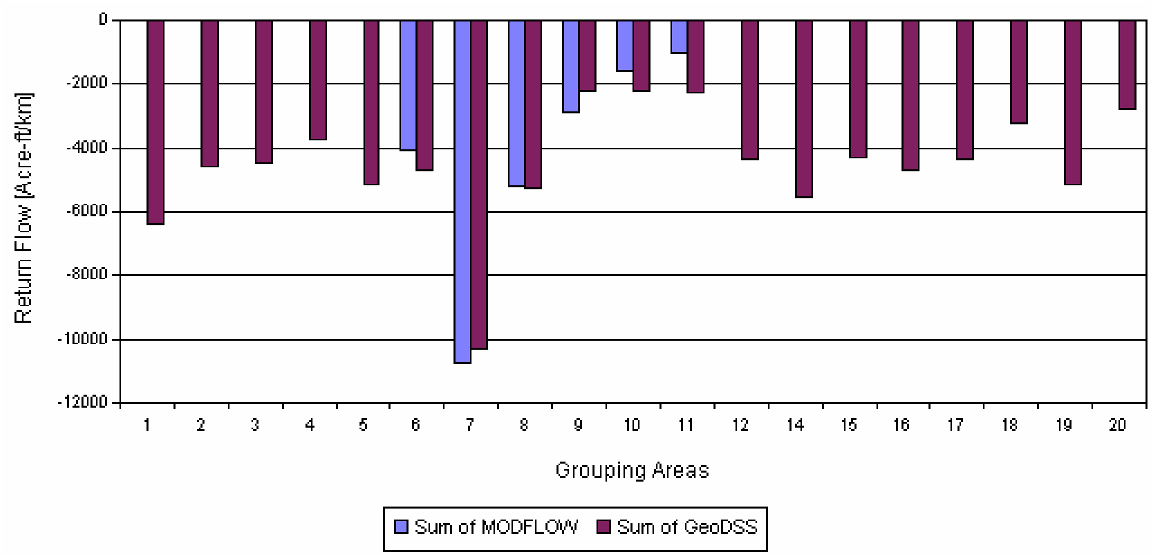

Figure 6.27 – Basin-wide Arkansas River stream-aquifer interaction modeling summary

Tributaries stream-aquifer interaction

The *LAR GeoDSS* tributary return flows and concentrations were compared with the MODFLOW calculations. Figure 6.28 shows total net aquifer return flows during the three-year calibration period for those grouping areas with tributary modeling. The average RMSE for the four-modeled areas = 8.98 acre-ft/km. The prediction error analysis per year is shown in Figure 6.29, with the largest error of 12.77 acre-ft/km (RMSE) occurring in grouping area 6 during the first year of simulation and 6.48 acre-ft/km over the remaining two calibration years.

With the exception of grouping area 11, the *LAR GeoDSS* average predicted concentrations tend to be lower than the MODFLOW modeled concentrations in all the grouping areas (Figure 6.30). In this case, analyzing the concentration error per calibrated-year shows no clear difference in the concentration prediction performance for the grouping areas (Figure 6.31). It is noticed that in both analyses (i.e., for individual years and the overall performance), there is a sequence of larger concentration prediction errors in the grouping areas in the downstream direction. It is believed, however, that this behavior would not provide a reasonable basis for generalizing predictions over the entire basin.

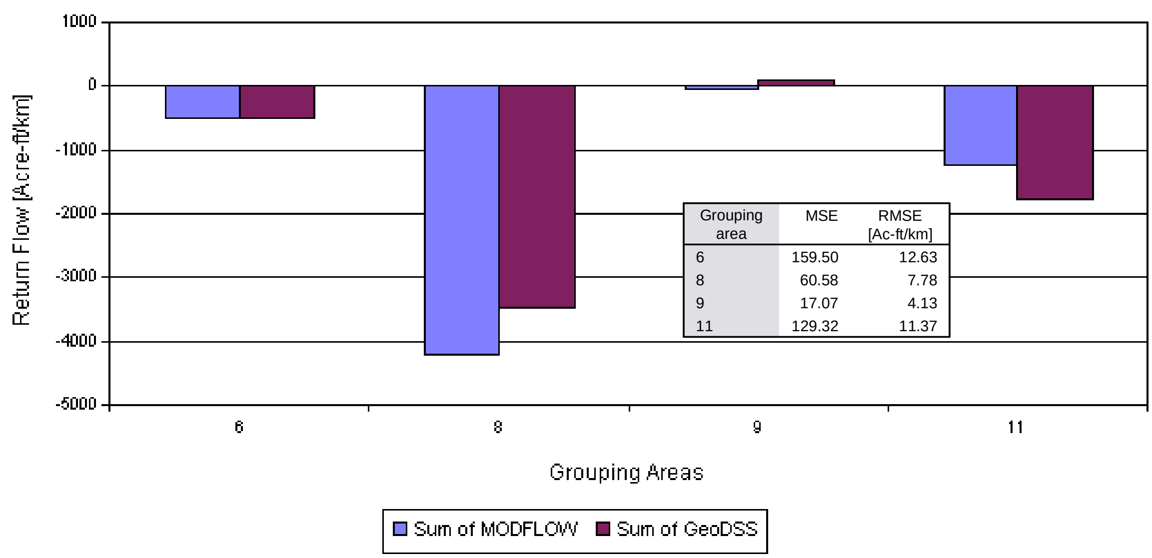

Figure 6.28 – Tributary total net return flow comparison for the modeled grouping areas

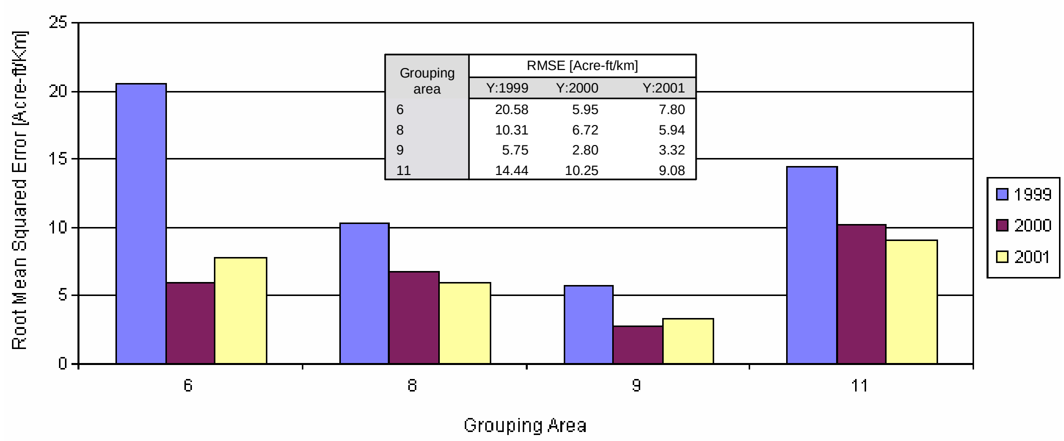

Figure 6.29 – Tributary aquifer return flow RMSE per year per grouping area

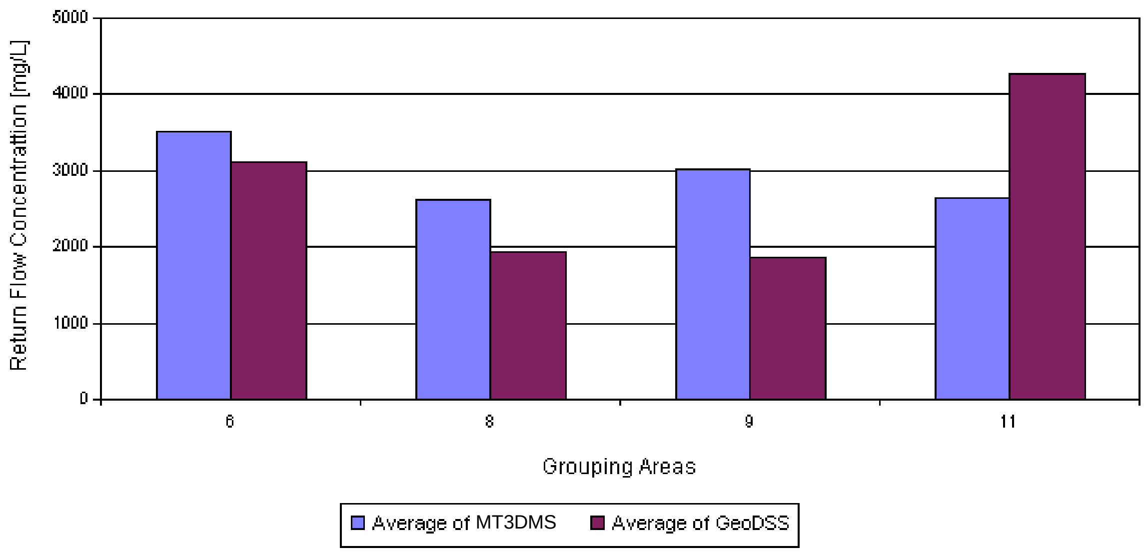

Figure 6.30 – Tributary Average concentration comparison for modeling grouping areas

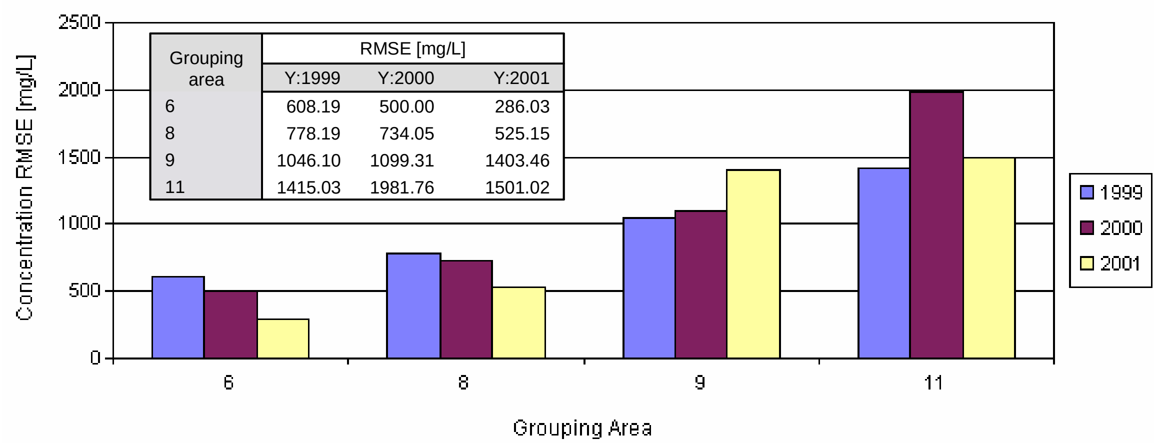

Figure 6.31 – Tributary Concentration RMSE per grouping area per year

The basin-wide tributary stream-aquifer interaction shows that total predictions for MODFLOW-MT3DMS non-modeled grouping areas are in the modeled range, with larger return flows predicted in the downstream region of the modeled area (Figure 6.32). Grouping Area 7 was excluded from the ANN training because less than 1 km of tributary length is intercepted by the grouping area; therefore the return per unit length is not representative. The *LAR GeoDSS* prediction was only calculated if the length is greater than 1 km, i.e., grouping area 7 stream-aquifer interaction prediction was omitted in the *LAR GeoDSS* modeling.

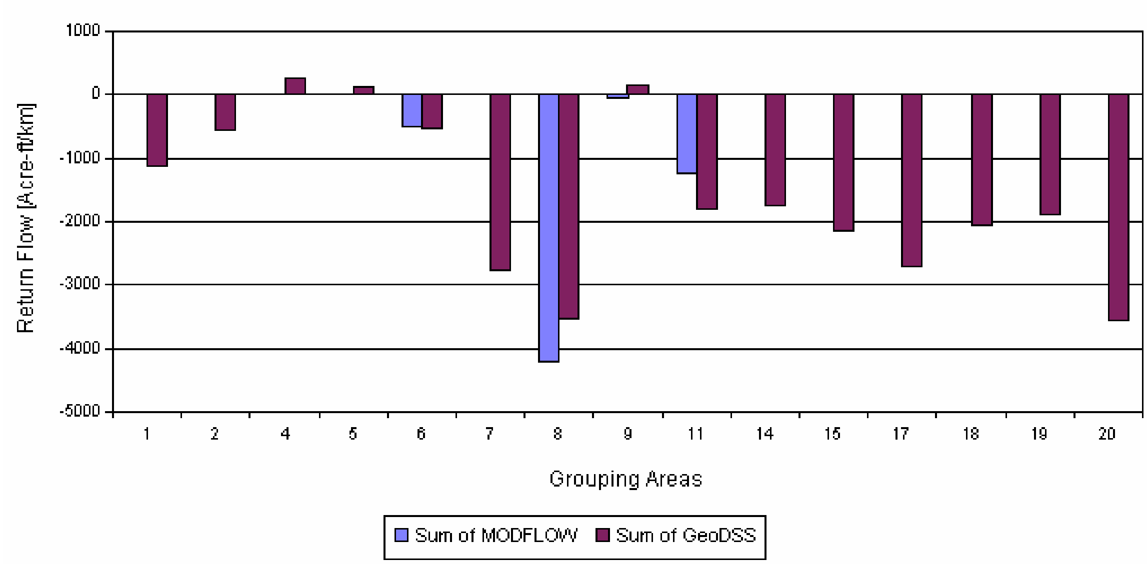

Figure 6.32 – Basin-wide tributary total net return flow summary

Analysis based on Calibration Reaches

The goal of the calibration is to estimate the network unmeasured gains and losses. Without specifically modeling the stream-aquifer interaction in the *LAR GeoDSS*, the computed gains and losses are based on streamflow measurements that include the aquifer return flows and river depletions. An analysis of the calibration results with and without the ANN stream-aquifer modeling provided information for the ANN prediction analysis.

System Source Reaches Analysis

The system source analysis without stream-aquifer interaction gives the surface measured inflows to the system at their corresponding gauging stations (Table 6.15). Analyzing Figure 6.33 and Figure 6.20, the reaches APIFOWCO, BIGLAMCO, HUEBOOCO, STCHARCO, WILDHOCO, and TIMSWCO show a groundwater contribution that is a portion of the surface measured based gains. Reaches CANSWKCO (Crooked Arroyo) and HRC194CO (Horse Creek) show a groundwater contribution larger than the measured flow in Figure 6.33, indicating a possible over-prediction of return flows in these tributaries. Since both CANSWKCO and HRC194CO were partially contained in the groundwater modeled area, it was possible to check the MODFLOW-MT3DMS results to examine the situation.

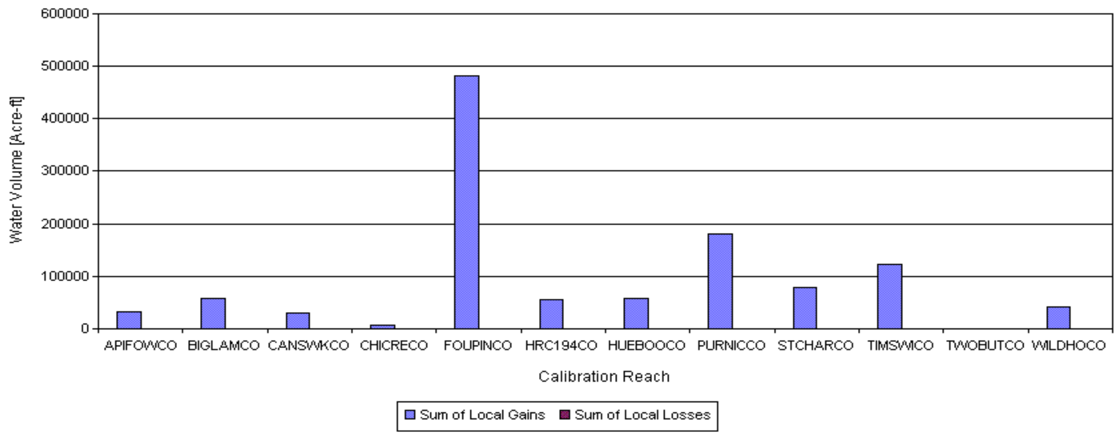

Figure 6.33 – System source reaches inflows without stream-aquifer modeling

Table 6.15 – Net System Source Reaches Inflow Summary

Reach	Inflows [Acre-ft]	Losses [Acre-ft]
APIFOWCO	32801	0
BIGLAMCO	57636	0
CANSWKCO	29289	0
CHICRECO	6961	0
FOUPINCO	482964	0
HRC194CO	56018	0
HUEBOOCO	57573	0
PURNICCO	181259	0
STCHARCO	77903	0
TIMSWICO	122147	0
TWOBUTCO	290	0
WILDHOCO	41035	0

The Geo-MODFLOW tool was used to extract the MODFLOW return flow volumes to Crooked Arroyo upstream of the station. Comparison of the measured amounts, the MODFLOW return flows and the ANN predicted return flow volumes show that over-prediction occurred at Crooked Arroyo in the *LAR GeoDSS* simulation (Figure 6.34). The ANN predictions for tributary return flows (per unit length of tributary reach) in the grouping area represent the MODFLOW total return flow in the tributaries of grouping area

8 quite well (as shown in Appendix II – *All_Scen_GWR_v8Trib_a Overall and Baseline Predictions Analysis*). However, since the volume is evenly distributed over the nodes on the tributaries in grouping area, the small tributaries (e.g., Crooked Arroyo) could have received a portion of the return flows that was disproportionally large for their size, while large tributaries (e.g., Timpas Creek) received a smaller return flow for their size. Figure 6.35 supports this hypothesis by showing the larger MODFLOW return flows and smaller *LAR GeoDSS* predictions at Timpas Creek (i.e., larger tributary in grouping area 8). The limitation illustrated in this exercise reiterates the expected low accuracy of stream-aquifer interaction predictions at smaller scales than the modeling grouping areas.

Figure 6.35 shows that the MODFLOW return flow volumes were generally larger than the measured gains, indicating a groundwater model over-prediction in Timpas Creek.

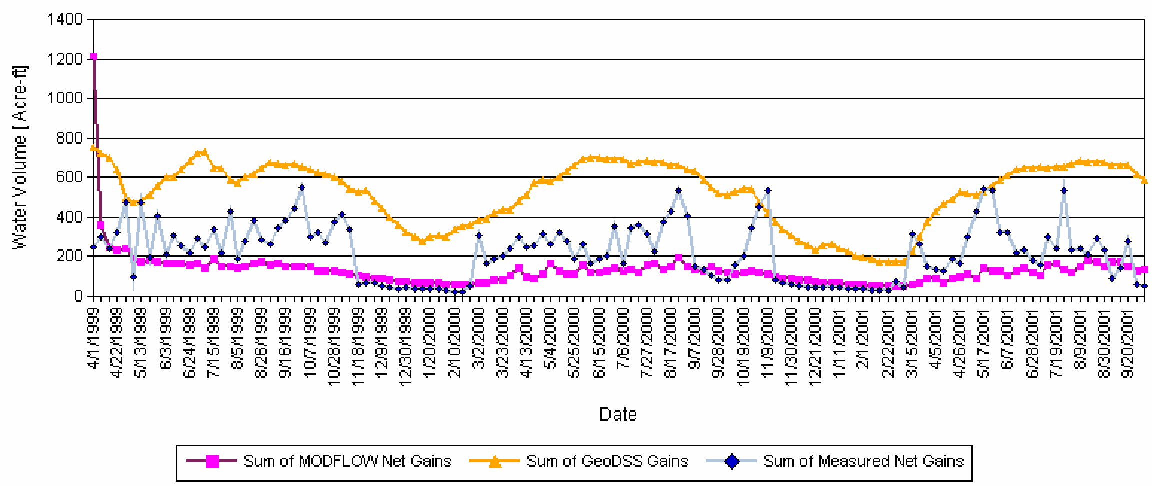

Figure 6.34 – Crooked Arroyo return flow comparison

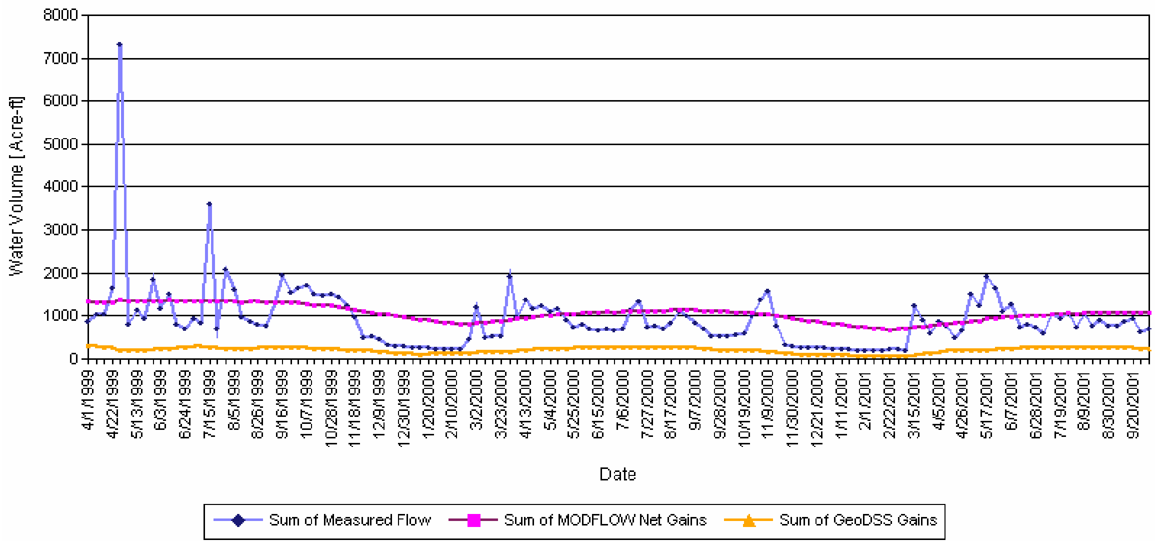

Figure 6.35 – Timpas Creek return flow check

The section of Horse Creek in the irrigated valley upstream of the station *HRC194CO* extends for about 23 km, with the length of the creek inside the two area-buffers about 11 km. Since the explanatory variables for stream-aquifer interaction were calculated only in the area-buffers, it is believed that the prediction was over estimated by using the entire length of the creek in the irrigated valley to predict the return flows. A more accurate prediction should be calculated with a shorter tributary length in the grouping area (approximately one-half); to provide better agreement with the measured values.

Intermediate Reaches Analysis

Network calibration was performed without the ANN stream-aquifer interaction, with the gains and losses calculated in this calibration exercise shown in Figure 6.36 and Table 6.16. Using the ANN stream-aquifer interaction modeling, the calibrated local losses increased in magnitude and the local gains reduced in magnitude, indicating that there could have been more total aquifer return flows than the anticipated from the surface water reach balance. This suggest that there could have been a timing issue in the return flows and possibly an over prediction. This analysis was affected by stations having zero flows (i.e., time steps without flow measurements) since the calibration algorithm opens the station to allow predicted flows to continue downstream. This situation forces the removal of additional losses at the immediate downstream control point. As a consequence, comparison of gains and losses with predicted return flows should combine these types of calibration reaches in order to be meaningful. As shown in Figure 6.21, stream-aquifer interaction was not modeled in Fountain Creek and the Purgatoire River (FOUPUECO, PURHILCO, and PURLASCO), so the results in Figure 6.36 show the outcome of upstream measured inflows in relation to the measured flows at these stations. The FOUPUECO reach reveal a losing/gaining section, PURHILCO shows a predominant losing reach, and PURLASCO indicate a predominantly gaining reach.

Table 6.16 – Calibrated Gains and Losses without Stream-Aquifer Interaction Modeling

Reach	Inflows [Acre-ft]	Losses [Acre-ft]
ARKAVOCO	156804	49981
ARKCACCO	137469	49901
ARKCARCO	104087	6152
ARKCOOKS	169804	10104
ARKGRACO	85154	23051
ARKJMRCO	50107	120550
ARKLAJCO	148037	27649
ARKLAMCO	96488	12852
ARKLASCO	148972	4658
ARKMOFCO	40858	27137
ARKNEPCO	133161	49610
ARKROCCO	132362	72550
FOUPUECO	30786	16126
PURHILCO	1664	55976
PURLASCO	21551	1374

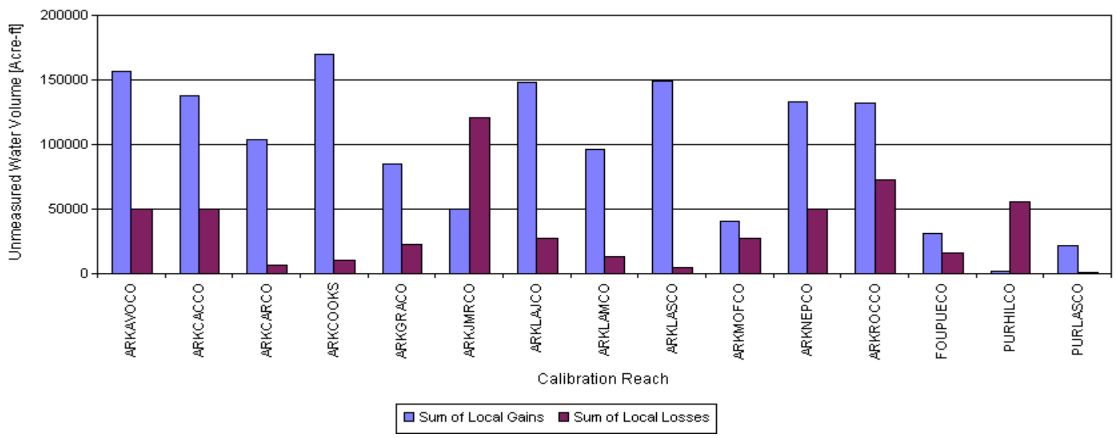

Figure 6.36 – System gains and losses for calibration without stream-aquifer interaction modeling

Three reaches intercept the groundwater modeled area: (1) ARKLAJCO, (2) most of the ARKROCCO and (3) a portion of the ARKLASCO. Stream-aquifer interaction predictions in these reaches were expected to be the closest to the MODFLOW-MT3DMS calculated interaction because they were located in the groundwater modeled area. Figure 6.37 shows net gains to these reaches from groundwater in both the MODFLOW-MT3DMS and *LAR GeoDSS* results as compared with the net gains calculated based on the surface water mass balance calculations. The results show that the *LAR GeoDSS* predictions were close to the MODFLOW net return flows, whereas the measurement-based net gains were more variable with positive (gains) and negative (losses) spikes. The average net gains during the modeled period in this reach were: 1283.60 acre-ft, 1028.27 acre-ft, and 945.19 acre-ft for MODFLOW, *LAR GeoDSS* and measurement-based respectively. Assuming that most of the measured gains were due to the groundwater-surface water interaction, the averages indicate a slightly tendency in MODFLOW and the *LAR GeoDSS* to over predict return flows in the long run.

Figure 6.38 shows the ARKROCCO reach comparison for the net gains calculated in MODFLOW, the *LAR GeoDSS* and the measurement-based surface water balance. The MODFLOW and *LAR GeoDSS* results show some agreement in their predictions, but the measurement-based mass balance show high variability and small agreement with the MODFLOW and *LAR GeoDSS* predictions. Since no measured data were available at ARKROCCO prior October 1999, the *LAR GeoDSS* disabled the station during this period to allow flows to continue downstream. This situation created losses in this reach that were caused by excess flows in the downstream reach, with gains in this period estimated to only meet historical diversions. The average net gains of MODFLOW, *LAR GeoDSS* and measurement-based mass balance were: 1283.60 acre-ft, 1917.22 acre-ft and 419.95 acre-ft respectively.

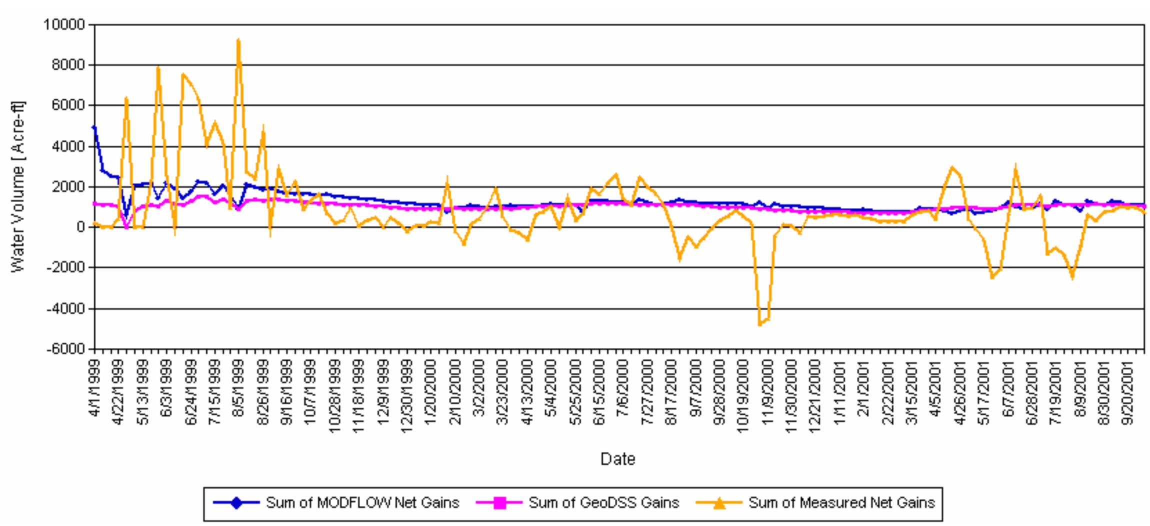

Figure 6.37 – ARKLAJCO reach return flow comparison

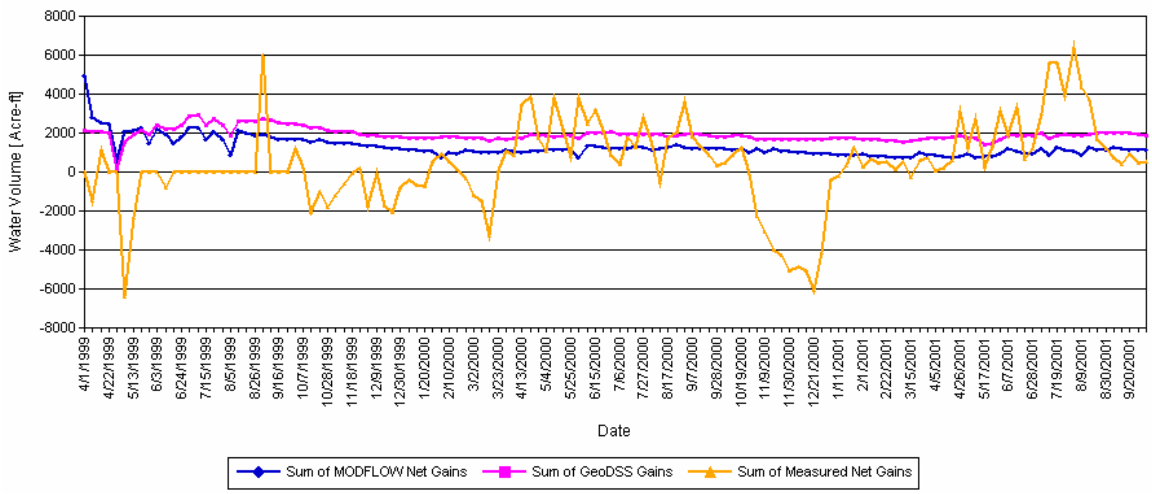

Figure 6.38 – ARKROCCO reach return flow comparison

Figure 6.39 shows a comparison of the modeled and measured net gains for the ARKLASCO reach, indicating a good agreement between net gains calculated in MODFLOW, *LAR GeoDSS* and measured surface water reach balance. The largest disagreement and highest variability was seen at the initial time steps of the modeling where large spikes were calculated from the measured data.

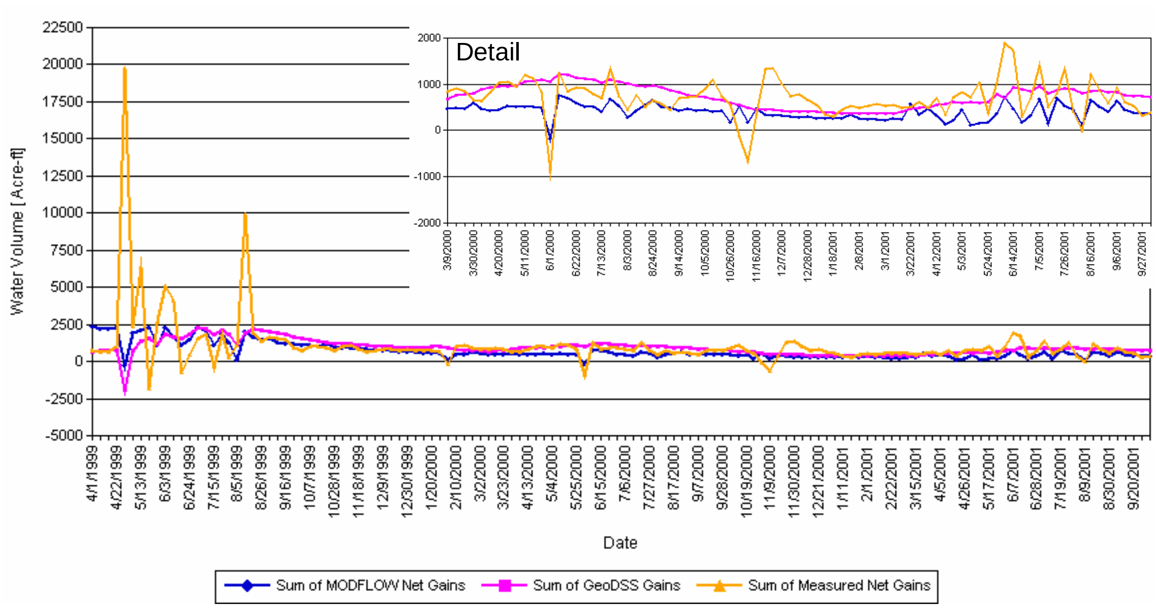

Figure 6.39 – ARKLASCO reach return flow comparison

Interpreting the comparison for ARKROCCO and ARKLASCO reaches requires taking into account that the entire area was not modeled in MODFLOW (see Figure 6.19). Consequently, the MODFLOW net return flows were calculated based only on the modeled cells. Detailed plots for the gains and losses per time step with and without the stream-aquifer interaction modeling are found in Appendix V – *Detailed Gains and Losses Analysis*.

Water Quality Calibration Analysis

During calibration, the ANN-predicted flows and concentrations were assigned as known system inputs and outputs. Consequently, an excess of modeled salt contributions from the aquifer to the surface system was compensated for during calibration by assigning low concentrations to reaches with unknown sources of salt mass; i.e., system measurements or calibrated inflows without concentrations defined. In this section, the calibrated water concentrations at the control points with measured specific conductance were compared with the measured values to evaluate the effectiveness of the semi-automatic calibration procedure. For the calibrated results, the cases where calculated concentrations were greater than the measured concentrations, the number and magnitudes of the unknown inputs were insufficient to dilute flows in the reach and match the measured value, recalling that unknown concentration limits lain between 0 and the maximum field observed value. In contrast, for cases where the calculated concentrations were lower than the measured concentrations, the unknown concentrations at the maximum allowed concentration were not high enough to elevate the concentrations in the reach to match the downstream-measured concentrations. Time series plots of the calculated and measured concentrations for all the reaches in the *LAR GeoDSS* can be found in Appendix V – *Water Quality*

Calibration Detailed Analysis. The root mean squared error (RMSE) was calculated with the predictions for all the modeled time steps at the water quality control points in the basin (Figure 6.40). The RMSE values give a sense for the magnitude of the expected error in the water quality calibration. The errors were larger in the more downstream stations since the calibration errors accumulate in the direction of the flow; i.e., the modeled concentration was continuously computed through of the control points, propagating the unmatched concentration downstream until there were enough unmeasured inputs to overcome the discrepancies with measured concentrations downstream.

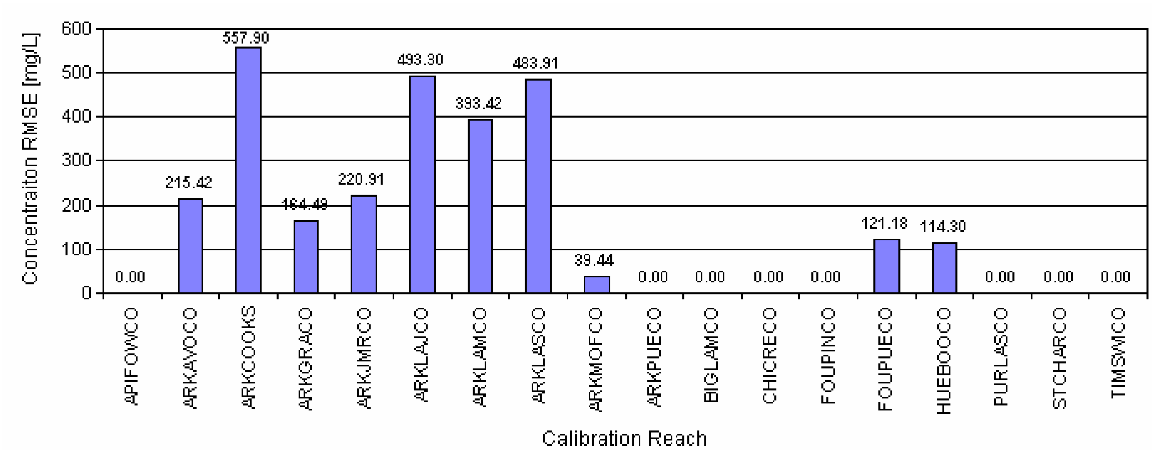

Figure 6.40 – Root Mean Squared Error (RMSE) at the *LAR GeoDSS* control points

The average concentration at the control points provided a measure of over or under prediction of concentrations in the calibration results. Figure 6.41 and Table 6.17 present a summary of the statistics of the predicted and measured average concentrations at the control points in the modeled Arkansas River basin. Based on the average concentrations, reaches ARKKAVCO, ARKGRACO, ARKLAJCO, ARKLASCO and HEBOOCO tend to be over-predicted, whereas concentrations in ARKCOOKS, ARKJMRCO, ARKLAMCO, ARKMOFCO and FOUPUECO were general under-predicted. The coefficient of determination was also calculated for the concentration predictions at the gauging stations. For most of the control points, the proportion of the variability accounted for in the calibration procedure ranged from 0.6 to 1, except for the FOUPUECO station that r^2=0.35. Even though the FOUPUECO calculated concentrations match the measured concentrations in several time steps, these cases where concentrations were not matched resulted in under-prediction that produced a low error r^2 overall. The measured and predicted averages were separated by only by 60 mg/L and the standard deviations were similar, indicating that the predictions were reasonable despite the low coefficient of determination.

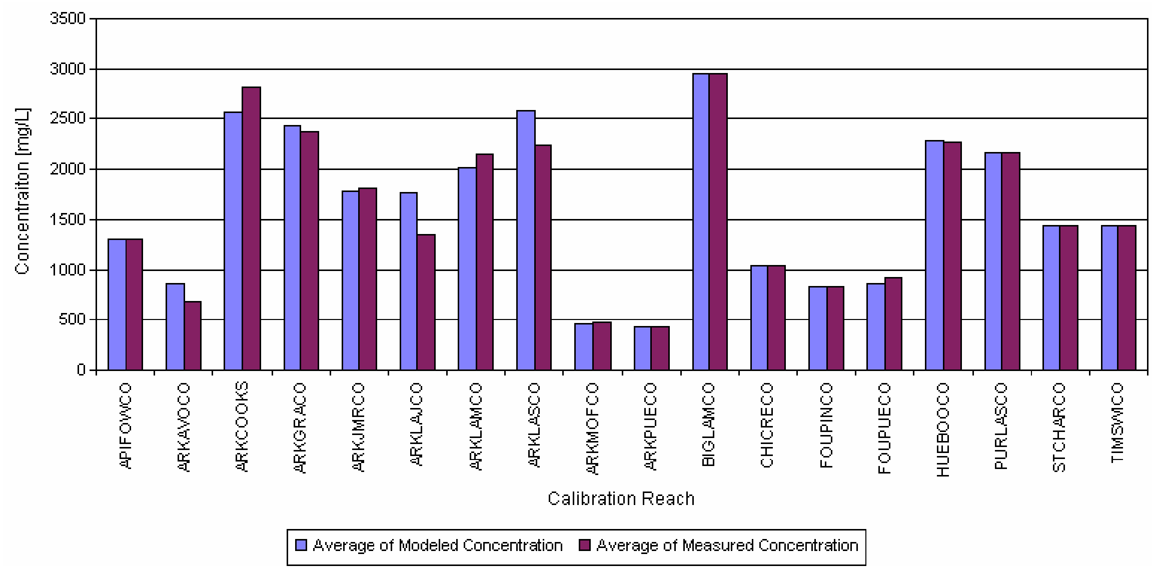

Figure 6.41 – Average calibrated and measured concentration comparison

Table 6.17 – Calibrated Concentration Statistics per Control Point

Reach	Modeled Concentration Average [mg/L]	Modeled Concentration Standard Deviation	Measured Concentration Average [mg/L]	Measured Concentration Standard Deviation	Average Difference	R^2
APIFOWCO	1304.05	220.16	1304.05	220.16	0.00	1
ARKAVOCO	865.05	244.67	689.36	152.82	-175.69	0.87
ARKCOOKS	2569.88	489.73	2815.04	700.76	245.16	0.57
ARKGRACO	2426.54	410.45	2367.64	343.00	-58.90	0.87
ARKJMRCO	1786.23	344.14	1807.87	218.82	21.64	0.60
ARKLAJCO	1771.09	448.18	1349.86	324.68	-421.23	0.70
ARKLAMCO	2023.46	335.88	2152.88	518.33	129.42	0.48
ARKLASCO	2582.50	784.64	2241.85	686.24	-340.65	0.79
ARKMOFCO	461.10	78.84	471.16	93.12	10.06	0.84
ARKPUECO	422.92	53.26	422.92	53.26	0.00	1
BIGLAMCO	2956.00	303.63	2956.00	303.63	0.00	1
CHICRECO	1034.97	327.47	1034.97	327.47	0.00	1
FOUPINCO	831.66	108.66	831.66	108.66	0.00	1
FOUPUECO	865.45	114.98	924.82	117.41	59.37	0.35
HUEBOOCO	2278.11	627.15	2267.58	612.57	-10.52	0.97
PURLASCO	2161.13	387.36	2161.13	387.36	0.00	1
STCHARCO	1443.38	304.15	1443.38	304.15	0.00	1
TIMSWICO	1445.61	307.38	1445.61	307.38	0.00	1

ARKJMRCO was computed using the ANN-based algorithm for the reservoir water quality transport. As anticipated during development of the ANN-based predictions (Chapter 4 – *The Simulation Challenge*), the results show that the ability of the ANN to predict measured concentrations at the reservoir outlet is affected by alterations in the explanatory variables. That is, concentrations at the reservoir inlets change as result of the inability to match the measured values during the water quality calibration. Although the explanatory variables for calibration of reservoir salt transport modeling reflected slightly different conditions than occurred historically, the ANN reservoir outlet concentration predictions followed a close trend with the measured concentrations (Figure 6.42), giving some confidence in the consistency of the predictions despite changes in system conditions. The simulation runs presented the ANN with variations in the baseline scenario (i.e., historical conditions), which dictated changes in the concentrations downstream of the reservoir. The reservoir salt transport modeling plays an important role in the analysis of the management alternatives.

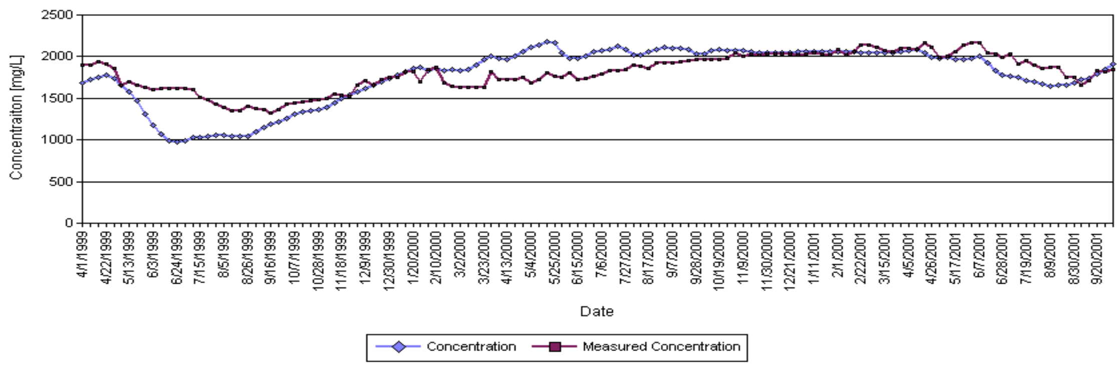

Figure 6.42 – ANN-based John Martin Reservoir water quality transport results

Deliveries based on Water Rights

During calibration, the Arkansas River modeling system allocated available flows to the demands based strictly on the specified water rights. The MODSIM consumptive demands were set to the maximum amount deliverable at each point. The water right decree amounts assigned as capacities on the links conveying flows to the nodes served to limit the amounts delivered at each time step. In this exercise, the reservoirs were set to meet historical storage levels by assigning these targets as the highest priority in the system. Storage contracts and alternate points of diversion were modeled with higher priorities than other water rights, and therefore these historical flows were preserved in the simulation. Water allocation differed from the historical records when an entitled diversion did not occur historically, which affected water available in the system for all diversions with more junior water rights. In this case, differences between the historical and calculated diversions across the basin show significant differences, exemplifying the uncertainty introduced by the human component influencing the water diversion operations. As a consequence, the consumptive water demand time series were used in the simulation to provided additional information to the water rights allocation, thereby maintaining the system operation as close as possible to the historical conditions. Further investigation of these operational uncertainties was not pursued in this study. For future work, the *LAR GeoDSS* tool can be applied to comparing strict water rights allocation with historical occurrences to further investigate the source of situations that might be causing of the differences between the expected and actual diversions.

MODEL SIMULATION

The baseline simulation network was created using the Base-Network with the same settings as the calibration network, i.e., enabling the ANN-based stream-aquifer interaction, the John Martin Reservoir salt transport modeling, and the *LAR GeoDSS* water quality module. The network simulation implemented the calibration flows and salt loadings computed during the calibration step as fixed system inflows and outflows. Simulation was carried out in two reservoir operational modes: (1) using the historical volumes in the reservoirs as storage targets, and (2) using a MODSIM reservoir layer balancing set up.

Reservoir Modeling Mode A

This modeling mode used the *LAR GeoDSS* Base-Network defaults, i.e., the reservoir historical volumes as storage targets and the priorities of 500 and 600 for Pueblo Reservoir and John Martin Reservoir respectively. As expected, these results show full agreement between the calibration and simulation flows and concentrations, demonstrating the adequate implementation of the simulation algorithm using the calibration flows and salt loadings. Pueblo and John Martin Reservoirs operated according to the specified targets in this case (Figure 6.17 and 6.18). No shortage occurred in the baseline simulation run for demands having water shortages during calibration since the baseline simulation recalculated water demands equaled the actual water supplied during calibration. For the improved water management alternatives demands were adjusted according to the characteristics of the scenario (e.g., reduction in areal recharge or reduction in seepage).

Reservoir Modeling Mode B

In this reservoir modeling mode, the reservoir storage space was divided into storage layers that store water using incremental costs assigned to each layer. The cost of the system reservoir layers were set up to fill the reservoir layers in such pattern that system storage is balanced between the reservoirs. The storage target was set to the maximum volume since the incremental costs assigned to the reservoir layers drives the allocation of water. The node priorities and layer costs were adjusted to manage the operation of the reservoirs in similar fashion to the historical operation. In this simulation mode, a calibrated network was used to provide historical flows through the control points, while using the reservoir layer to store water in the system reservoirs. The cost adjustment process showed that Pueblo Reservoir required slightly higher priority (1760) than John Martin Reservoir (1800), with the corresponding storage link cost of -32000 and -32400 respectively. Ten layers were defined for modeling both John Martin and Pueblo Reservoirs, with the layers defined as a percentage of the reservoir capacity, where John Martin Reservoir capacity was 701,755 acre-ft and Pueblo Reservoir capacity was 357,000 acre-ft. Table 6.18 shows the definition of the layers in John Martin Reservoir and the associated incremental costs. Table 6.19 gives the Pueblo Reservoir layers and costs.

The ANN prediction sensitivity was tested using this operational mode. The stream-aquifer interaction modeling was simulated for comparison with both ANNs trained as described in Chapter 4, corresponding to Datasets A and B. The Dataset_B was trained using the flows in this system operational mode. The use of the Dataset_B ANN required re-calibration of the system using historical reservoir storages and calculation of the corresponding gains and losses that match the measured flows, whereas the ANN for Dataset_A used the Mode A calibration.

Table 6.18 – John Martin Reservoir Layers Definition and Incremental Cost

Initial Volume	Ending Volume	Capacity Percent	Cost	Total Cost
0	140351	20	200	-31800
140351	210526.5	30	266	-31734
210526.5	280702	40	333	-31667
280702	350877.5	50	400	-31600
350877.5	421053	60	466	-31534
421053	491228.5	70	533	-31467
491228.5	561404	80	600	-31400
561404	631579.5	90	800	-31200
631579.5	666667.25	95	1000	-31000
666667.25	701755	100	1500	-30500

Table 6.19 – Pueblo Reservoir Layers Definition and Incremental Cost

Initial Volume	Ending Volume	Capacity Percent	Cost	Total Cost
0	71400	20	300	-32100
71400	107100	30	366	-32034
107100	142800	40	433	-31967
142800	178500	50	500	-31900
178500	214200	60	566	-31834
214200	249900	70	633	-31767
249900	285600	80	700	-31700
285600	321300	90	900	-31500
321300	339150	95	1100	-31300
339150	357000	100	1600	-30800

Using the Mode A calibration and the Dataset_A ANN, the reservoir storage as a result of this operational mode is shown in Figures 6.43 and 6.44 for Pueblo and John Martin Reservoirs, respectively. The calibration storage corresponds to the historical storage in this case, which is provided for performance comparison. This reservoirs operational mode stored larger volumes in Pueblo Reservoir, and consequently smaller volumes in John Martin Reservoir. The operation resulted in an extremely low level in John Martin Reservoir, which should be improved in the future for more realistic simulation. Since the calibrated local gains and losses were computed based on the historical measured flows, simulations for this operational mode assumed that the historical hydrological and operational conditions on which the calibrated flows were based remained unchanged in this simulation (e.g., precipitation, end of the field runoff, canal operational flows.)

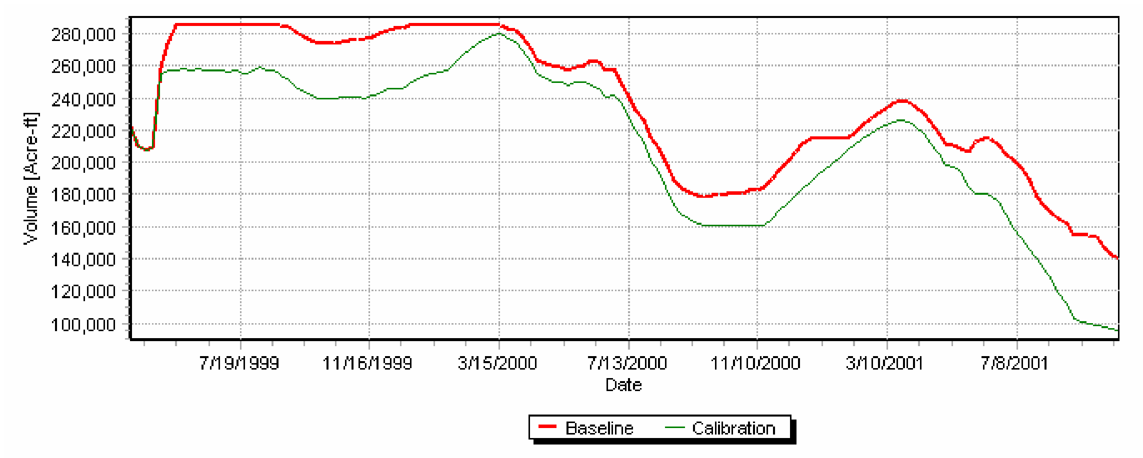

Figure 6.43 – Pueblo Reservoir storage in Mode B simulation

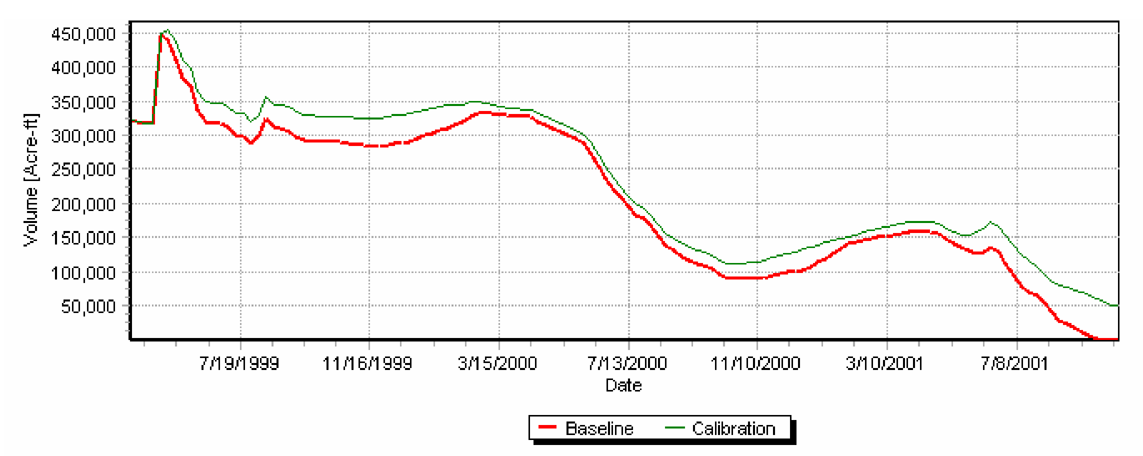

Figure 6.44 – John Martin Reservoir simulated storage in Mode B

A comparison of selected simulation indicators was carried out to verify the algorithm key elements and observe the stream-aquifer interaction sensitivity in this simulation mode to both small changes in modeling conditions and ANN training and number of recurrent variables. Table 6.20 shows a summary of selected simulation indicators for the baseline simulations in operational mode B with different ANNs for stream-aquifer simulation, as well as, the calibration network in operational mode A for comparison. Storage at the end of the simulation was the same in Mode A and Mode B with Dataset_B, indicating that the same total amount of water is stored in the system, even though, in operational mode B the reservoir storages are different than the historical. The end-of-simulation storage was lower in the Mode B with Dataset_A simulation because this network used the calibration from Mode A. In this case, the ANN generated lower net return flows, thereby causing a reduction in storage at the end of the simulation (Figures 6.43 and 6.44). The total system demands were the same in the compared runs, with zero shortages in the baseline simulation runs as expected. The baseline simulation network in Mode B, with the ANN used in Mode A, changes the way water was moved in the system. Therefore, the stream-aquifer interaction modeling explanatory variables were affected and consequently small variations in the return flows and concentrations could be observed in the results. The overall stream-aquifer interaction modeling results show a low sensitivity of less than 1%, to small variations in the MODSIM dependent explanatory variables (i.e., streamflow).

Small sensitivity was also observed in the predictions using ANN from Dataset_B in the simulation, demonstrating the consistency in the predictions generated by the priming algorithm that avoids having large errors due to accumulation of errors using recurrent variables from the *LAR GeoDSS* predicted values (Dataset_B contained a larger number of recurrent variables). The total local gains and losses decreased in the calibration for Mode B with Dataset_B with respect to calibration Mode A. A detailed summary per reach of simulation gains and losses and the percent of change from the calibration cases is presented in Table 6.21. Few calibration reaches show percent changes larger than 2%, but in general changes were a small percentage of the calibration gains and losses. Additional flows to Kansas at the Colorado-Kansas border were handled by the additional sink node connected to the Coolidge Station as discussed previously. This node collected any additional flows in the system that cannot be stored in the reservoirs. This simulation mode generated small additional flows to Kansas, most likely coming from return flows close to the border that could not be adjusted by the calibration links.

Table 6.20 – Operational modes Indicators Comparison

Stream-Aquifer Interaction ANN		Dataset_A	Dataset_B	Dataset_A
Simulation Indicator	**Units**	**Mode A**	**Mode B**	**Mode B**
End System Storage	[Acre-ft]	145182.0	145192.0	139931.0
Total Diversion	[Acre-ft]	3027545.0	3027545.0	3027545.0
Total Diversion Shortage	[Acre-ft]	0.0	0.0	0.0
Diversion Avg. Conc	[mg/L]	1271.6	1233.9	1232.6
Canal Seepage	[Acre-ft]	605509.0	536691.2	605509.0
Total Kansas Flow	[Acre-ft]	975814.0	975804.0	975804.0
Kansas Avg Conc	[mg/L]	2590.3	2539.8	2538.3
Total Return Flow	[Acre-ft]	1717562.0	1704669.0	1711713.0
Return Flow Avg Conc	[mg/L]	2768.7	2768.5	2768.5
Arkansas River Return Flow	[Acre-ft]	1148182.0	1141118.0	1144117.0
Arkansas River Ret.Flow Conc	[mg/L]	2796.0	2794.3	2796.0
Tributaries Return Flow	[Acre-ft]	569380.0	563551.0	567596.0
Tributaries RetFlow Conc	[mg/L]	2698.4	2699.1	2695.4
Total River Depletion Flow	[Acre-ft]	19654.0	25954.0	19169.0
River Depletion Avg Conc	[mg/L]	1816.1	1684.8	1801.5
Arkansas River Depletion	[Acre-ft]	4511.0	4524.0	4281.0
Arkansas River Depletion Conc	[mg/L]	1230.9	1186.4	1189.3
Tributaries Depletion	[Acre-ft]	15143.0	21430.0	14888.0
Tributaries Depletion Avg Conc	[mg/L]	1957.1	1780.2	1945.6
Total Local Losses	[Acre-ft]	1205633.0	1196815.0	1205625.0
Total Local Gains	[Acre-ft]	1939539.0	1943164.0	1939539.0
Total Calib Flow In	[Acre-ft]	2959868.0	2966962.0	2959868.0
JMR Total Mass In	[Tons]	1710820.0	1415548.0	1415909.0
JMR Total Mass Out	[Tons]	2172141.0	2142178.8	2129815.0

The Mode B (Dataset_B) water quality calibration show a slight increase in mean squared error (Figure 6.45) with respect to the calibration network (Figure 6.40). An exception is the localized RMSE increase at ARKLASCO and ARKMOFCO control points caused by a higher number of reach zero flow events in the Arkansas River that reduced the dilution effect on the contribution of salt loadings from the tributaries. Figure 6.46 shows the average simulated concentrations in Mode B (Dataset_B) as compared with the measured concentrations at the *LAR GeoDSS* control points.

Table 6.21 – Detailed Simulation Gains and Losses per Calibration Reach Mode B with Dataset_B ANN

Reach	Inflows [Acre-ff]	Losses [Acre-ft]	GW Return Flow [Acre-ft]	River Depletion [Acre-ff]	% Calibration Change	
					Inflows	Losses
ARKAVOCO	51005	89061	146730	1851	-0.01	0.19
ARKCACCO	57959	106961	138930	2360	0.15	0.25
ARKCARCO	23611	43749	142305	2343	0.21	-0.04
ARKCOOKS	54933	66780	171757	210	-0.13	0.30
ARKGRACO	24319	39690	55585	0	0.15	0.09
ARKJMRCO	42495	130141	17347	144	0.00	0.01
ARKLAJCO	33451	105973	136075	270	-10.47	-0.67
ARKLAMCO	13951	104642	174327	0	1.44	0.19
ARKLASCO	55864	35173	127066	3443	0.01	1.77
ARKMOFCO	37925	29772	5568	0	-0.01	0.01
ARKNEPCO	71218	123012	138381	3036	0.04	-0.21
ARKPUECO	1366378	0	0	0	0.00	0.00
ARKROCCO	56054	185105	257445	4502	8.28	0.57
FOUPUECO	30786	16126	0	0	0.00	0.00
PURHILCO	8062	56015	0	0	37.11	-0.29
PURLASCO	15153	1335	0	0	-12.59	13.71

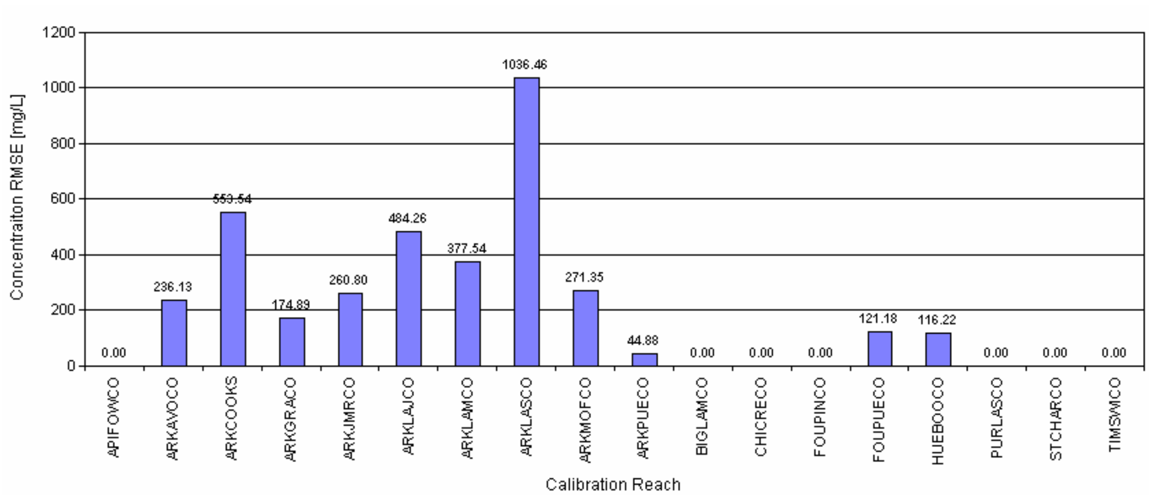

Figure 6.45 – Simulated water constituent concentration RMSE summary at the *LAR GeoDSS* control points

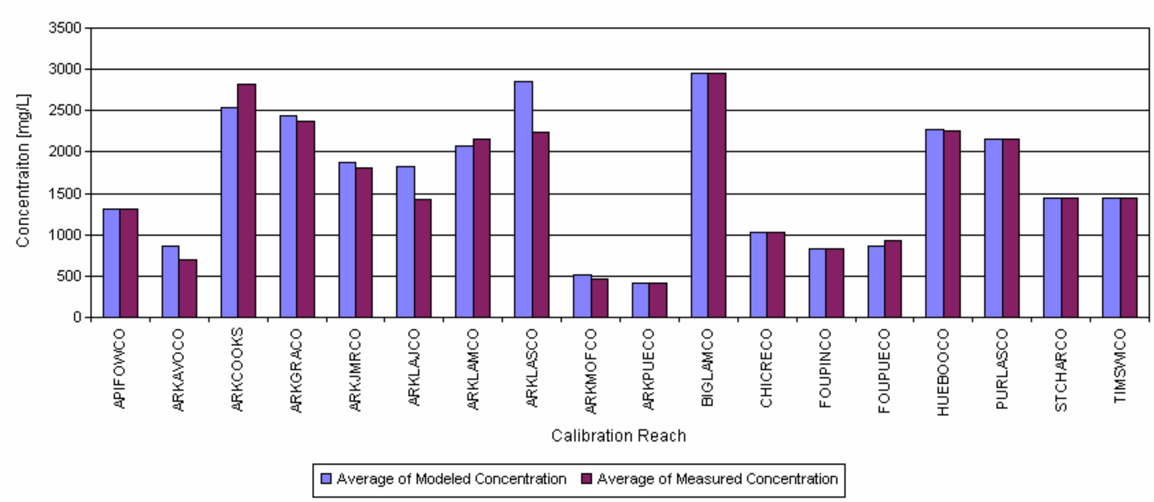

Figure 6.46 – Average concentration prediction at the *LAR GeoDSS* control points
Mode B (Dataset_B)

REMARKS

Simulation of the ANN-based stream-aquifer interaction appears to closely represent the MODFLOW-MT3DMS calculated return flows and TDS concentration for the modeled reaches. However, it was found that the ANN provided gains reduced the surface water balance based gains, but at the same time, an increase in water loss. This situation suggests an over-prediction of the return flows and/or timing issues. The calibration analysis reveals a stream-aquifer interaction modeling weakness in accurately representing tributary return flows. When the sizes of the tributaries in a grouping area are significant, over predictions are expected in the smaller tributaries and under-prediction in the larger ones. In addition, it was noted that over prediction of return flows occurs in tributaries extending considerably their stream-aquifer modeled lines outside the area-buffers in the grouping area since the explanatory variables were captured only in the area-buffers that is stresses outside the area-buffers diminished since return flows per unit length of tributary are expected to reduce outside of the irrigated valley, which was not considered in the current algorithm.

The water quality calibration algorithm was unable to fully match the measured concentrations at the control points, because of the combination of inflows with unmeasured concentration magnitudes and calibration concentration limits restricted the process. The larger discrepancies are found in reaches with few or small unmeasured inflows and gains. The unmatched measured concentration occurrences propagated the calibration-calculated concentrations downstream, potentially increasing the difficulty of matching the next downstream measured concentrations. The overall water quality calibration performance show a reasonable set of modeled concentrations at the control points where, in most cases, more than 60% of the variability was explained. In the most downstream stations, the highest root mean squared error is around 500 mg/L. A small tendency to over-predict concentrations at control points where discrepancies were found indicate that there should have been more dilution in the reach that what was currently modeled.

Water allocation based solely on water rights generated discrepancies with historical diversions due to unexpected human operations of the system (e.g., not diverting entitled water), causing a cascading effect on all the more junior water users resulting in large inconsistencies basin-wide with the historical diversions. Diversion records time series are recommended to keep the water rights water allocation in track and closely simulate historical conditions.

The ANN-based stream-aquifer interaction modeling show low sensitivity to changes in average river flows, which were used extensively as explanatory variables (four previous values were used as shown in Figure 4.16). This characteristic gives confidence in the stability of predictions on small variations in the explanatory variable space.