CHAPTER 5

CONJUNCTIVE GROUNDWATER AND SURFACE WATER QUANTITY AND QUALITY MODELING APPROACH IN *RIVER GEODSS*

STREAM-AQUIFER INTERACTION MODELING APPROACH

A common practice in the analysis and modeling of basin scale stream-aquifer interaction is an excessive simplification due to the cumbersome development of detailed models at this scale. Analytical approaches primarily rely upon a number of conceptual simplifications, thereby increasing the uncertainty and inaccuracy of the results [e.g., the CALVIN model (Howitt 1999)]. Common assumptions include simplified aquifer geometry and significant constraints on aquifer physical characteristics such as homogeneity, isotropy, time invariance, and infinite (or semi-infinite) aquifer extent. In contrast, finite difference and finite element numerical methods can accurately represent the time-variant, heterogeneous physical system, but are computationally intractable when appropriately applied over large areas.

A popular method to model stream-aquifer interactions at the basin scale is the stream depletion factor (SDF) method (Jenkins 1968). The SDF is a spatially variable system descriptor with time dimension, which indicates the time it takes for 28% of the depletion (or return flow) to occur, for predicting volumetric changes in streamflows due to recharge or withdrawal of water from the aquifer. The SDF method aggregates spatially-varied hydraulic properties, aquifer stress locations, and complex boundary conditions. Sophocleous (1995) compared the numerical finite difference model MODFLOW (McDonald and Harbaugh 1988) with SDF method and reported considerable discrepancies between the two approaches in representing a real-world stream-aquifer system. These results were corroborated by Fredericks et al. (1998), finding significant differences using groundwater response coefficients developed from the SDF method as compared to a finite difference groundwater model. The *River GeoDSS* includes tools required to directly link the MODFLOW-MT3DMS modeling cells comprising the finite difference grid with MODSIM objects, thereby taking advantage of the various geo-processing tools that can be applied on geo-referenced objects. However, this approach to conjunctive use modeling is considered impractical at the basin scale and therefore of limited use for evaluation of management alternatives. The methodology introduced herein represents stream-aquifer interaction at basin scale, but is founded on a regional-scale MODFLOW-MT3DMS groundwater modeling calibrated with extensive field data. Artificial neural networks are utilized to model the stream-aquifer interaction (as described in Chapter 4), with the trained ANN used to predict representative grouping area return/depletion flows and salt loadings. The methodology is computationally efficient and economically feasible, with an accuracy compromise as a function of the extent of the basin to be applied to outside of the groundwater modeled area.

BASIN-SCALE WATER QUALITY MODELING

The use of relationships between flow and specific conductance, total dissolved solids and other ions (Cain et al. 1987; Sandhu et al. 1999) has been used to develop hydrologic water quality models in the Arkansas River basin. Cain et al. (1987) developed useful regression relationships between flow and specific conductance for several stations in the Arkansas River basin. This approach is limited, however, for accurately representing aquifer responses to management alternatives since the developed relations are based on historical events. These relations lack the ability to represent changes in system characteristics, which limits their use to the historical system conditions only. A more robust and comprehensive approach is sought for conjunctive use water quality modeling in the *River GeoDSS* to better handle management alternatives analysis that are not constrained to historical conditions.

The existing Arkansas River Valley MODFLOW-MT3DMS groundwater flow and water quality model takes into account the physical system characteristics and complex water quality constituents modeling in the unsaturated zone, allowing accurate prediction of system responses to management changes. Ideally, the *River GeoDSS* water quality modeling should include changes in the base-flow quality for management alternative comparison. Using the trained ANN stream-aquifer interaction model for management alternative simulation, it is possible to predict changes in groundwater contributions for both the main stem and the tributaries and analyze changes in base-flow conditions during these simulations. The most upstream water quality-measured points in the basin are modeled as water quality constituent sources. Baseline regression equations, similar to Cain et al. 1987, can be developed for the system sources and control points when only sporadic water samples are available. Even though the groundwater contributions will accommodate changes in the system dynamics during the simulation of the management alternative, the baseline regression equations assume that the same baseline conditions (i.e., all other flow and water quality constituent contributions) remain constant.

CONJUNCTIVE SURFACE-GROUNDWATER QUANTITY AND QUALITY MODELING

As the primary engine of the *River GeoDSS* Modeling subsystem, MODSIM provides great flexibility to accommodate complex operational aspects and provides the tools for realistic water resources system simulations under water rights and institutional constraints. In addition, the MODSIM version 8 modular design and .NET integration (Labadie 2006) allows coupling into other environments and models, thereby providing a flexible platform for enhanced modeling systems by attaching modules to the main model engine. In addition, the modular design allows development of customized graphical interfaces, such as the Geo-MODSIM interface described in Chapter 3. For example, the *River GeoDSS* Water Quality Module (WQM) providing conservative constituent modeling throughout the system, tightly linked with MODSIM flows and can interact with the ANN module to include its predictions in the water quality routing.

The *River GeoDSS* couples all its components to provide an innovative conjunctive groundwater surface water quantity and quality modeling platform. A trained ANN for stream-aquifer interaction (e.g., the ANN presented in Chapter 4) is made available in the modeling system through the *River GeoDSS* ANN Module. The ANN simulation dataset for all the modeled grouping areas is built into the *River GeoDSS* from the training files, system characteristics and MODSIM modeling variables. The ANN stream-aquifer modeling is incorporated into MODSIM by making use of the Geo-MODSIM spatial representation of the network. The Geo-MODSIM network is prepared to be coupled with the ANN by populating the data-model objects with: (1) a flag to indicate the type of ANN stream-aquifer modeling, i.e., main river or tributaries; and (2) the corresponding stream-aquifer modeling grouping area ID. The ANN provides water and salt accretion/depletion volumes per time step for each grouping area along the main stem and tributaries. These predictions are evenly distributed among the MODSIM nodes in each grouping area. The predicted flows and corresponding concentrations are incorporated into the MODSIM network using connecting links with an ANN source/sink support construct (as described in Chapter 3) where flows are provided to the MODSIM network as inputs and outputs of the system, where the predicted flows and concentrations are used in the WQM as mass sinks and sources for the system. The MODSIM water allocation process dynamically includes the ANN-predicted flows. Since these flows are a function of the MODSIM modeled water allocation, the ANN predictions are based on actual system states for the modeled simulation scenario. The WQM is set up to route conservative water constituents from the most upstream points in the system to downstream locations via mass balance calculation on: (1) the ANN-predicted groundwater salt loadings and (2) the ANN-based reservoir salt transport calculation. Figure 5.1 shows a schematic diagram of the conjunctive surface groundwater quantity and quality modeling approach employed in the *River GeoDSS*.

Johnson (1998) remarks that numerical methods are valid and useful when calibrated and used for the same area but have limited capabilities in representing more generalized cause and effect relationships to which they were calibrated. Numerical methods are highly dependent of the system configuration and boundary conditions, since these characteristics are “hard-wired” into the problem and therefore the results. It is well known that ANNs, despite their powerful pattern recognition capabilities, are essentially a sophisticated regression model which treats the physical mechanisms governing the natural system as a “black-box.” Such a model is therefore incapable of, or poorly suited to, extension to cases other than those for which it was trained (Suen and Eheart 2003). ANNs have been developed with normalized explanatory variables to perform predictions from explanatory variables spaces that are not training-area specific. For example, the relative elevation of the land in the first area-buffer with respect to the average elevation of the main stream is in a variable space that can be found in different grouping areas without being specific to the training region. The predictions normalized per unit length or unit area of a stream create a similar effect in which the predicted values are applicable to other areas of different size and shapes from the training areas. In conclusion, it is believed that the ANN model design allows discovery of relationships between normalized explanatory variables and normalized outputs than can be applied in other areas in the basin without necessarily extending the training cases.

The ANN used in the *River GeoDSS* for stream-aquifer interaction modeling is trained on a numerically modeled area to recognize patterns between system state changes (i.e., stresses) in the surrounding areas and responses at the modeled interface. The extracted relationships are applied to predict interactions at the interface in both the modeled and neighboring non-modeled areas. The ANN becomes a powerful predictor since it indirectly captures all aspects modeled in the finite difference groundwater model, including detailed non-saturated zone flow and salinity modeling. In this sense, the method does not require inflexible constraints/assumptions and lumped and/or poorly evaluated parameters found in many of the simplified basin scale return flow prediction methods. Since, the ANN is trained based on historical combination of stresses; (i.e., weekly pumping, combined seepage and recharge combined, and calibrated stream-aquifer responses), the system states used for the ANN are realistic and physically based.

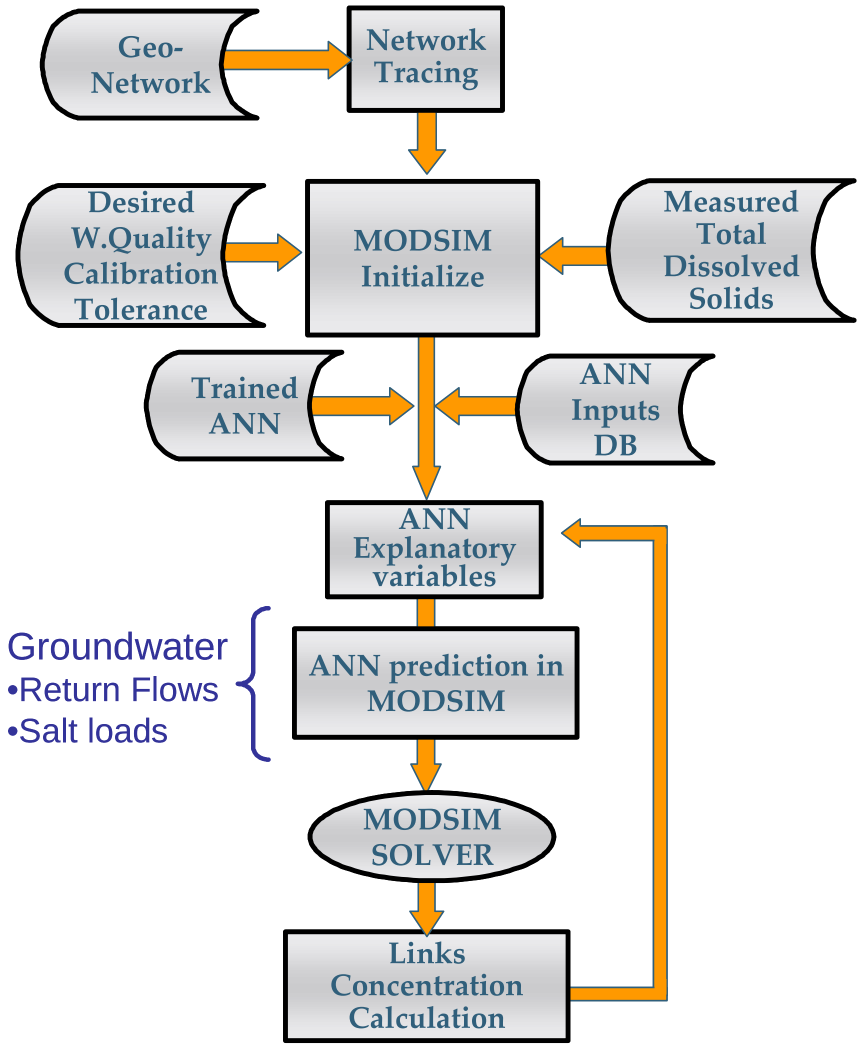

Figure 5.1 – *River GeoDSS* conjunctive quantity and quality modeling diagram

Hydrologic Calibration Tools

The *River GeoDSS* features a set of tools for both experienced and inexperienced users to carry out conjunctive surface and groundwater river basin modeling using Geo-MODSIM as the modeling framework. This section describes the types of networks used to calibrate and simulate the network. Appendix III – *MODSIM Network Execution Pre-processing* provides details of internal network manipulation for automating calibration and simulation.

Network Calibration

The *River GeoDSS* provides the tools to construct a Geo-MODSIM calibration network that is capable of quantifying for any network the local gains and losses required to match measured flows at the stream gauging stations. Local gains and losses represent unmeasured flows in/out of the system, such as unmeasured tributary flows, surface runoff from precipitation and irrigation; evaporation, subsurface irrigation return flows, drainage from irrigated fields, and seepage. The local gains and losses also account for measurement errors at gauging stations and points of diversion. The Geo-MODSIM active gauging stations, i.e., stations with available measured flow for the simulated period, are used to create calibration reaches in the modeled basin. Calibration reaches are defined as sections of the river/stream where water is measured at upstream and downstream ends, with each reach composed of all nodes and links traced upstream from a gauging station until other gauging stations are found (on tributaries or the main stem).

Figure 5.2 shows the schema of a calibration reach structure in a MODSIM flow network. The structure contains a source/sink construct connected to all the gauging stations, where excess flow upstream of the station is removed and flow deficiencies at the gauging station are augmented as local gains to the downstream reach. The source and sink nodes are connected by a link that is assigned a negative cost to encourage direct flow from the source to the sink, thereby assuring that only flows required to match the gauged flows are included. The stations are modeled as *flow-through* demands with the measured flows provided as the *flow-through* demand time series, with the immediate downstream link closed. A special case that is implemented when the gauging station lacks measured data sets the time series to zero, thereby preventing flow through the node. In this situation, the algorithm opens the closed-downstream link to allow flow from the upstream reach, where calibration is performed at the next measured downstream gauging station.

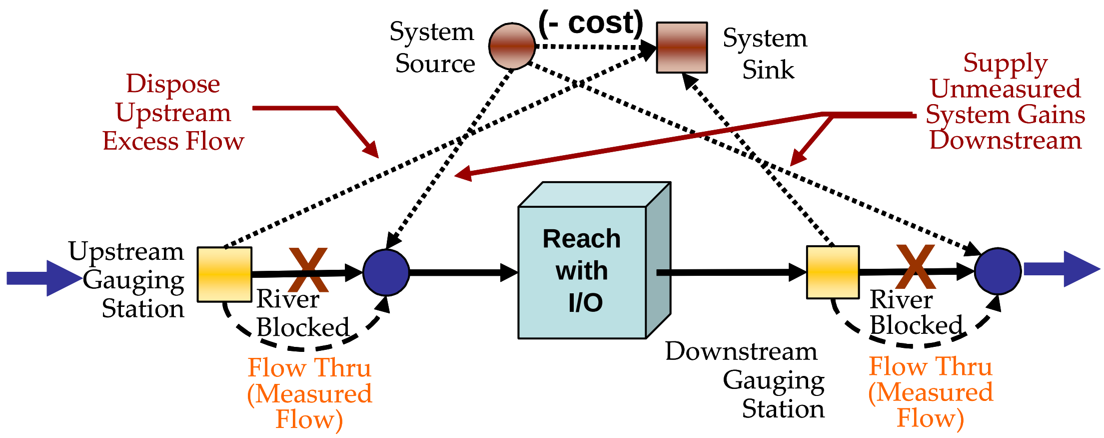

Figure 5.2 – Schematics of the calibration structure for a reach in Geo-MODSIM

During calibration, water is allocated according to MODSIM model settings (i.e., costs and priorities), but only within each reach, since the calibration reaches are isolated from each other. The calibration run is set to completely satisfy the water user demand (usually historical measured diversions) and meet reservoir storage targets, since local unmeasured gains and losses are provided using the system source/sink construct as shown in Figure 5.2. During calibration, water shortages can occur when there are inconsistencies between the measured diversion and the water right entitlements, including the storage water contracts.

A special calibration structure is implemented for the most upstream gauging stations (Figure 5.3) that avoids having water shortages at the most upstream stations by providing a source link to the *flow-through* demand node. A small positive cost is assigned to the link providing local gains to encourage flow through the gauging station. In this case, no excesses are expected upstream of the station, so the link from the most upstream station to the system sink is not implemented.

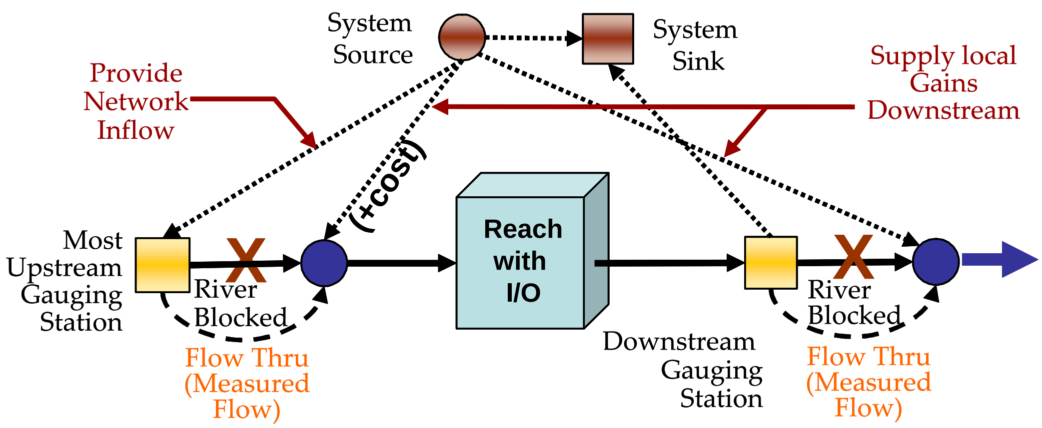

Figure 5.3 – Schematics for the most upstream reach calibration structure

The calibration mode is activated for the active scenario in the *River GeoDSS Model* tab (Figure 5.4).

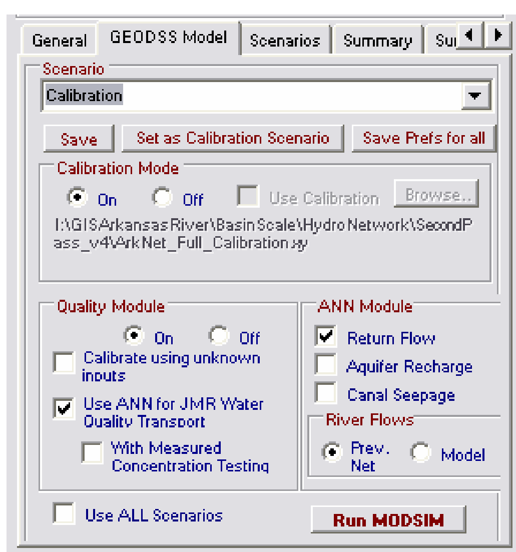

Figure 5.4 – *River GeoDSS* modeling preferences user interface (calibration mode)

Stream-Aquifer interaction modeling in calibration

The ANN-based stream-aquifer interaction modeling can be included in the calibration procedure (using the options in Figure 5.4). In this case, the ANN modeling structures are created and the predicted interaction is represented as additional inflows and outflows at the system nodes. The water allocation process and quantification of local gains and losses, in each reach includes groundwater return flows and depletions. When the stream-aquifer interaction is active, the calibration structures quantify the local gains and losses by excluding the aquifer stream interaction and providing only the additional water needed to remove the excess. Errors (i.e., over/under predictions) in the ANN stream-aquifer predicted flow values are balanced out in the *River GeoDSS* model calibration by removing excesses and adding additional required water.

Semi-automatic Water Quality Calibration Tool

Differences between the measured and modeled concentrations at the control points provide a measure of the magnitude of the correction required (e.g., upstream unmeasured water quality constituent load contributions) during model calibration. At the control points, concentrations can be lowered by adding water of lower concentrations and can be increased by adding more saline water to the reach. The *River GeoDSS* features a water quality semi-automatic calibration tool, which uses the WQM mass routing algorithm (including the ANN reservoir salt transport model) to model concentrations and calculates the modeled concentration deviation from the measured values at the gauging stations. The calibration procedure adjusts the unknown water concentrations in the system (i.e., sources of water with unmeasured water quality) to match as closely as possible the measured concentrations. The water quality calibration process has a large degree of freedom, but is kept realistic using node-based user-controlled concentration ranges. Water quality calibration is triggered in the *River GeoDSS* by checking the box *Calibrate Using Unknown Inputs* (Figure 5.4). When not used during model calibration, the WQM provides water constituent routing using available concentrations, while assuming zero concentrations for the unknown concentrations. Details on the water quality calibration procedure are located in Appendix IV – *Implementation of the Water Quality Calibration*.

The calibration tool accommodates groundwater contributions as predicted by the ANN module by providing salt loads at the system sources (i.e., the most upstream measured stations) that result in computed and measured concentrations agreeing. At system sources with upstream aquifer contributions, which are common on tributaries with gauging stations, the calibration procedure assigns a concentration value to the source link that results in the baseline measured concentration downstream of the station and retains the baseflow as predicted by the ANN. The source link concentrations are not changed during the management scenario simulations, but groundwater contributions can change, thereby affecting contributions from the tributaries (baseflow) during the simulation scenarios.

Simulation Networks

Two simulation modes are available in the *River GeoDSS*. The first is the standard MODSIM run, in which water is allocated using the included time series and network flow preferences. In this case, the *River GeoDSS* calibration structures are not created, making the user responsible for providing the inflow time series and calibration flows. The second mode performs river basin simulation that automatically includes the calibration results for add/remove of calculated local gains and losses (options in Figure 5.5). This feature is particularly useful for simulating “what if” management alternatives. The gains and losses computed during calibration are volumes that, according to the measured data, should have been present in the system to achieve mass balance. For the simulation mode, the flows are incorporated as fixed system inputs and outputs. This operation assumes that for management alternative simulation, the historical conditions that generated the gains and loses are replicated. In some cases, this assumption may introduce errors in the simulation. For example, if the management alternative includes significant changes in irrigation practices, flows at the ends of the canals, and/or the irrigation runoff, may differ from that portion computed in the calibration flows. The simulation of management scenarios using the baseline calibration flows allows comparison of alternatives using the baseline conditions as the default structure. Errors generated from changes in local gains and losses during implementation of the management alternatives are expected to be negligible since the major changes in system flows are accounted for in the simulation.

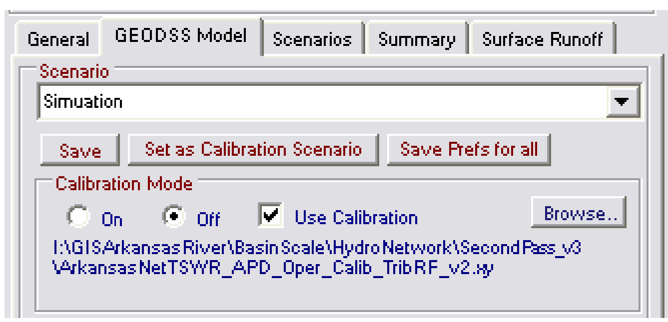

Figure 5.5 – User interface for selecting simulation mode using calibration results

During simulation, the calibration structures are created and adapted to allow modeling of the calibration inflow/outflows and simulate uninterrupted flow through the gauging stations by opening their downstream link, thereby allowing the basin-wide priorities and costs to dictate water allocation. Gauging stations are modeled as low priority *flow-through* demands, with the time series of calibration link upper bounds set to the computed flows from the calibration run. Figure 5.6 shows a diagram with the elements of the calibration structure in the simulation network.

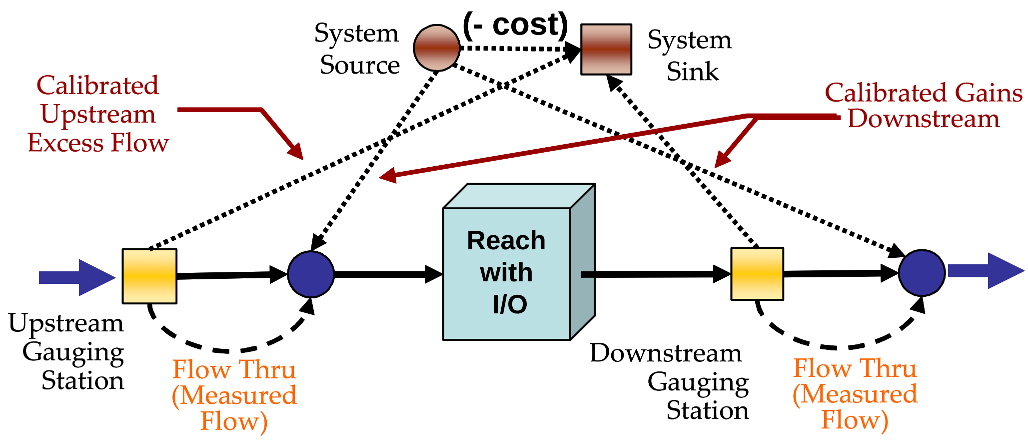

Figure 5.6 – Schematics of a calibration structure in simulation

Stream-Aquifer interaction modeling in simulation

As in calibration, the ANN module can be used in simulation to represent the stream-aquifer interaction. For each simulation, the ANN module builds the simulation dataset using the simulated management alternative conditions; therefore, the predicted return flow/depletions dynamically account for changes in the system conditions.

Water Quality Simulation

In the simulation run, concentrations calculated during the water quality calibration are assigned to the corresponding points. At each time step, the *River GeoDSS* uses the concentrations stored in the calibration network output file to set them as sources in the network. With all concentrations assigned, the WQM performs salinity routing continuously from the most upstream nodes to the system sink at most downstream end.

APPROACH AND APPLICATION DISCUSSION

The *River GeoDSS* methodology to model basin scale stream-aquifer interaction is a powerful alternative to traditional methods without requiring restrictive simplifications, extensive data requirements and cumbersome calibrations. The method employed in the *River GeoDSS* requires fewer resources and data than directly using basin scale distributed parameter models (e.g., MODRSP, MODFLOW or IGSM2), which are computationally intensive and require an extensive/expensive hydro-geologic data base, basin-wide monitoring, and intricate model calibration. Aquifer response coefficients derived at several points in the system using MODRSP (Maddock and Lacher 1991), or a vector-based approximation as in AQUATOOL, in which the eigenvector technique is used to represent the aquifer response (Andreu and Sahuquillo 1987), are methods better suited for a basin scale application when linearity assumption are acceptable. However, relying on a comprehensive underlying groundwater model (usually a distributed model), these methods can become impractical as well.

The conjunctive use modeling approach presented herein is applied in the *LAR GeoDSS*. In this study area, the previously developed SDF coefficients (Jenkins et al. 1972) are considered to be limited. The aquifer simplifications inherited from the Glover (1974) equations that use monthly time steps the SDF approach, and the simplified stream-aquifer model used in Jenkins study, are restrictive for accurately evaluating management alternatives in the basin. On the other hand, the current regional-scale groundwater model for the area (Burkhalter and Gates 2005, Burkhalter and Gates 2006), calibrated with extensive field data and including comprehensive salt modeling in the saturated and unsaturated zones for salinity remediation alternatives evaluation, perfectly suits the *River*

GeoDSS methodology, providing a useful resource to evaluate salinity management alternatives at basin scale.

Integration of the *River GeoDSS* components in both calibration and simulation allows state-of-the-art conjunctive groundwater and surface water quantity and quality modeling. The *River GeoDSS* modeling tools greatly simplify the calibration-simulation process, facilitating the evaluation of "what if" management scenarios. The dynamic usage of pre-calculated local gains and losses directly from the MODSIM output files, in conjunction with the simulation scenario manager, reduces the chances of large data management errors and expedites the simulation of management alternatives, and therefore, the decision making process.