CHAPTER 2

LITERATURE REVIEW

RIVER BASIN FLOW MODELING AND DECISION SUPPORT SYSTEMS

MODSIM is a generalized river basin network flow model (Labadie 2006), allowing not only representation of physical system features and processes, but also artificial and conceptual elements permitting flexibility in allocating water according to complex hydrologic, administrative, legal, and institutional/contractual mechanisms. MODSIM allows runs in calibration mode and in management mode, and includes stream-aquifer interaction modeling with user defined or model generated stream-aquifer response coefficients. The MODSIM Graphical User Interface (GUI) allow users to build the system topology, enter data and parameters and display the results in graphical or tabular form. The current interface lacks the ability of interacting with geo-referenced data directly. An outstanding MODSIM capability is that it allows customized code to be compiled with the main program, thereby enhancing flexibility in modeling complex behavior and rules and allowing integration of models and modules. It has been successfully applied in many river basins around the world encompassing institutional, administrative, and economic issues [e.g., the Gunnison River basin (Weiss et al. 1997), upper Snake River basin (Larson et al. 1997), South Platte River basin (Fredericks et al. 1998), Piracicaba River basin in Brazil (De Azevedo et al. 2000) and Friant Division

Project of the Central Valley Project in California (Marques et al. 2003)] . MODSIM is public-domain software that does not require a license purchase.

MODSIM can address environmental and water quality issues when used in conjunction with other models (Dai and Labadie 2001; Campbell et al. 2001; De Azevedo et al. 2000). MODSIMQ extends MODSIM to include surface water quality routing using an iterative connection with EPA QUAL2E (Brown and Barnwell 1987) and a soil column model for predicting salinity loading in irrigation return flows (Dai and Labadie 2001). MODSIMQ is able to model water quantity, water quality, and administrative/institutional aspects. QUAL2E is a 1D stream-water quality routing model (Brown and Barnwell 1987) able to simulate up to 15 water quality constituents, including dissolved oxygen, biochemical oxygen demand, temperature, algae as chlorophyll a, organic nitrogen as N, ammonia as N, nitrite as N, nitrate as N, organic phosphorous as P, dissolved phosphorous as P, coli form, an arbitrary non conservative constituent and three user define conservative constituents. The MODSIMQ groundwater component contains an unsaturated zone water quality model that accounts for chemical reactions, ion exchange and a steady-state saturated zone model with conservative assumptions for the transport of constituents. The groundwater component is a simplified representation of the complexity of basin scale modeling. It shares the MODSIM interface but lacks of a user friendly interface for QUAL2E. MODSIMQ assures convergence to a solution that maintains minimum water quality requirements. Although water allocation according to water rights priorities is included, MODSIMQ solution may adversely affect senior water rights since the primary goal is maintaining water quality standards. Dai and Labadie (2001) applied MODSIMQ to the LARV in Colorado for development of salinity control strategies. In this study, irrigation return flows, canal seepage, reservoir seepage, deep percolation, and river depletion due to pumping were modeled using stream depletion factors developed by the U.S. Geological Survey (Jenkins et al. 1972). The stream-aquifer interaction was modeled over monthly time steps, with major ion relationships used to estimate salt loads in the groundwater return flows similar to the approach presented by Cain et al. 1987.

RiverWare is an interactive object-oriented model to simulate all major river basin features including reservoirs, streamflows, diversions, and lagged returns flows (Zagona et al. 2001). It includes operational rules for reservoir releases and river diversions, and can be run using specified inflows and outflows, rule-based simulation, or optimization techniques. RiverWare uses the concept of a groundwater storage object that provides tools to model aquifer flow; however, the module's effective application requires detailed prior knowledge of system behavior or a detailed model to select the required object parameters. The RiverWare literature reviewed show an elaborate GUI but does not indicate the ability to geo-reference the model objects or use of spatio-temporal databases. This model lacks the ability to customize runs using outside programming code, thereby limiting its ability to be integrated with other models or modules. RiverWare is able to carry out water quality calculations by simulating total dissolved solids, temperature, and dissolved oxygen. For modeling total dissolved solids only, a simple, well-mixed model is also available. Temperature and DO models use a 2-layer reservoir model and discretized reaches in which the water quality equations are coupled with hydraulic routing, either with or without dispersion. RiverWare requires an expensive license and annual maintenance contract.

CALSIM is a generalized water resources simulation model for evaluating operational alternatives of large, complex river basins (Andrew et al. 2004). Originally developed by the State of California Department of Water Resources, CALSIM efficiently allocates water using a linear programming solver. Groundwater has only limited representation in CALSIM; it is modeled as a series of interconnected lumped-parameter basins. Groundwater pumping, recharge from irrigation, stream–aquifer interaction, and inter-basin flow are calculated dynamically by the model. Its GUI allows basic display of the system features, data, and plotting capabilities. CALSIM II, developed by the California Department of Water Resources in conjunction with the USBR, includes a GIS tool to execute the model from a GIS network. CALSIM integrates a simulation language for flexible operational criteria specification, but is unable to handle custom code for additional module integration. These combined capabilities provide a comprehensive and powerful modeling tool for water resource systems simulation. Even though CALSIM does not require a license, it needs commercial software to operate; plans to upgrade to a public-domain solver were found in the literature.

CE-QUAL-W2 is a finite difference water quality and hydrodynamic model in 2D (longitudinal-vertical) model for rivers, estuaries, lakes, reservoirs and river basin systems (Wells 2000a). CE-QUAL-W2 offers detailed water quality constituent modeling, including generic constituents [conservative tracers, water age or hydraulic residence time, coli form bacteria, and contaminants], inorganic suspended solids groups, phytoplankton groups, epiphyton groups, CBOD groups, ammonium, nitrate-nitrite, bioavailable phosphorus, labile dissolved organic matter, refractory dissolved organic matter, labile particulate organic matter, refractory particulate organic matter, total inorganic carbon, alkalinity, total iron, dissolved oxygen, organic sediments and gas entrainment. Accurate use of this model is limited by the discretization required in the finite difference models, thereby making it inefficient and difficult to apply to large basins.

MIKE BASIN is a river basin management tool in GIS developed by DHI Software (www.dhisoftware.com). That addresses water allocation, conjunctive use, reservoir operation, or water quality issues. This tool is designed to use GIS processing and display features coupled with hydrologic modeling for basin scale planning and management. Hydrologic modeling is achieved by representing the system using nodes and links. The new MIKE BASIN 2005 is implemented as an ArcGIS (ESRI®) extension with an integrated time series database. The model uses GIS geometric networks to represent the system topology, and the water allocation algorithm uses local or global rules to allocate water. The rules can define local priorities for riparian doctrines and global priorities for the prior-appropriation doctrine. MIKE BASIN is unable to handle delays in the flows in the global allocation of water such as occurring in groundwater modeling and channel routing. This tool calculates aquifer return flows to the stream using a simplified method based on a linear reservoir model with one or two aquifers (Fast/Slow response). The stream-aquifer interaction modeling requires the user to define time series corresponding to the stream seepage and the aquifer recharge. Realistic groundwater modeling in this tool is limited since the method is not linked with spatial-varied physical aquifer properties and spatial-temporal-varied system stresses such as recharge, sub-surface drainage and seepage. The water quality solution assumes purely advective transport, although decay during transport can be modeled. MIKE BASIN can model quality in the groundwater assuming in the conceptual model a perfect mixing in each aquifer (first order decay can also be modeled). MIKE BASIN allows user control of the simulation using VBA in ArcGIS; the ability to use this customization ability to link to other models or modules is not specified in the documentation. This commercial software requires the purchase of a license and ArcGIS as interface (stand-alone interface is not available).

Burns (1988) developed an interactive accounting model to simulate streamflow, water quality, and water supply operations in the Arkansas River basin. The model used regression equations to compute flow from incremental drainage areas by using a time series of independent variables, such as snow-pack, precipitation, or gauged flow. In this model the dissolved solids were computed from regression equations with streamflow as the independent variable. The model is applicable to a large lumped-area, thereby lacking the ability to analyze localized problems. The model as applied to the Arkansas Valley was calibrated to compute dissolved solids based on observed streamflow throughout the basin. Three sites in the basin were used for calibration in which daily specific conductance was used to determine observed monthly dissolved solids loads. Regression coefficients used for the calculation of dissolved solids were developed by Cain et al. (1987).

WEAP (Water Evaluation and Planning system) is a model developed by the Stockholm Environment Institute for water resources planning (Yates et al. 2005). The newest version features dynamic linkage with MODFLOW and QUAL2E for water quality modeling. WEAP introduces in this version the ability to use an Application Programming Interface to execute and control inputs/output of the model using programming code (including VBA, Visual Basic or scripting languages). WEAP claims to have objects geo-referenced but it is not reported whether the interface has GIS functionality for spatial data processing or display.

Decision support systems (DSS) are interactive programs, often with a graphical user interface (GUI), which embed traditional water resources simulation and optimization models, with adaptation of new approaches, to support users in semi-structural or ill-structural problem solving (Loucks and da Costa 1991). The Colorado River Simulation System (CRSS) model is implemented using the rule-based simulation capabilities in the RiverWare (Schuster 1989). The CRSS was developed in response to a need for a modeling system that could simulate operations for various hydrologic and demand sequences along the Colorado River. CRSS evaluates how proposed development occurring high in the basin might impact locations downstream from the development. The CRSS includes a flow simulation model of the entire Colorado River system. It also includes a stochastic natural flow model to generate future stochastic flows and a salt regression model that estimates natural salinity associated with natural flows.

A widely used DSS in Colorado is the Colorado's decision support system (CDSS), developed by the Colorado Water Conservation Board (CWCB) and State of Colorado Division of Water Resources (DWR) (CWCB and DWR 2002). The CDSS has been implemented in the Colorado River basin (CRDSS) (including divisions 4,5,6, and 7), the Rio Grande basin (RGDSS), and the South Platte basin (SPDSS) currently under development. These DSSs are centered on a database called HydroBase. The CRDSS focuses on surface water modeling and administration, the RGDSS extends the analysis to groundwater and surface water modeling. The CDSS includes (1) a surface water planning model (STATEMOD), (2) a consumptive water use model (STATECU (CWCB and DWR 2007)) that bases its estimates on spatial irrigation acreage data in a GIS and interacts with STATEMOD, (3) a web site for distributing project data and results, and (4) a number of other Colorado River modeling tools. The groundwater modeling efforts vary by basin; the RGDSS groundwater is modeled using MODFLOW, and the input data files are generated using: (1) basin GIS coverages and ArcView avenue pre-processing scripts, (2) the GMS model interface, (4) the STATECU model, and (5) the STATEMOD model. STATECU provides consumptive water use (CU), canal loss, surface water applied, and pumping based on historical data. STATEMOD allocates water under the prior appropriation doctrine based on user defined operating rules, providing the same data that STATECU uses to build the MODFLOW input files. From the literature reviewed, the CDSS lacks the capability for accurate modeling of the interaction between surface water and the groundwater. The groundwater model requires inputs from the surface water model, but it is not clear how the dynamic stream-aquifer interaction is modeled.

Mastin and Vaccaro (2002) developed a decision support system for the Yakima River Basin in eastern Washington. This DSS consists of three major components: a river and reservoir management model (RiverWare), a modular modeling system (MMS) that calculates runoff, and the central hydrologic database (HDB). The USGS MMS is an integrated system of computer software developed to provide a framework for the development and application of numerical models to simulate a variety of water, energy, and biogeochemical processes (Leavesley et al. 1996). The model for runoff prediction in the MMS is the USGS Precipitation-Runoff Modeling System (Leavesley et al. 1983). The HDB contains metadata and historical and real-time hydro-meteorological data. It allows for easy data query and display through graphical-user and data-management interfaces. The HDB acts as the bridge between RiverWare and MMS by accepting model input and output. The Yakima DSS uses a GIS interface, called Weasel (Leavesley et al. 1997), which is used to delineate watersheds and sub-basins, in addition to assisting in the construction of the model. Although the Yakima DSS utilizes detailed, spatially-varied data such as Digital Elevation Models (DEM), land use/land cover, soil layers, and forest-cover type and density, it lacks of detailed spatially-varied precipitation data for hydrologic modeling. The stream-aquifer interaction modeling is limited to determining percentages of total streamflow corresponding to surface runoff, sub-surface runoff and groundwater flow (Risley 1994), with the percentages varying according to the underlying soil of each sub-watershed. The Yakima DSS uses the Object User Interface to integrate the models, display data, initialize simulations, and transfer data to the database in an attempt to provide real-time operations support. No documentation was found for consideration or specific modeling of water quality aspects in this DSS.

Westphal et al. (2003) developed a DSS for short term planning (7 days) based on forecasted climatic conditions. The DSS is developed in Microsoft EXCEL and links a hydrologic model, reservoir hydraulic models, and a reservoir water quality model with linear and nonlinear optimization algorithms. The DSS offers the ability to optimize daily and weekly reservoir operations toward four objectives based on short-term climate forecasts: maximum water quality, ideal flood control levels, optimum reservoir balancing, and maximum hydropower revenues. Since there is no interaction between the DSS and a GIS, the DSS does not consider any spatially-varied information on the modeled basins. The stream-aquifer interaction is carried out using the *abcd* model developed by Thomas

(1981), which uses four physically-based parameters (*a*, *b*, *c*, and *d*) to estimate inputs and outputs from the aquifer and the surface soil moisture. Total organic carbon in one of the reservoirs modeled, but provides only coarse detail on the modeled basin, focusing primarily on the reservoir states. The literature does not indicate the ability of modeling detailed water allocation according to water rights.

McPhee and Yeh (2004) used groundwater simulation and optimization to construct a decision support system (DSS) for solving groundwater management problems in the Upper San Pedro River Basin (Arizona). A previously developed steady and transient finite difference model (MODFLOW) was used to simulate groundwater flow. The DSS provided a framework to aid decision makers in defining the best groundwater pumping and recharge policies in the basin by explicitly considering environmental, economic and development objectives.

Wurbs (2005) presents a package for river/reservoir system management (WRAP). This tool is implemented in Texas for assessing water resources availability and reliability, and is implemented to handle water allocation under water rights and analyze impacts of water management decisions. Work is reported on development of user interfaces and integration with GIS, but the main interface is limited to definition of input file locations, template generation, modules execution and linkage to HEC-DSSVue (USACE 2006), a Java-based GUI program for viewing, plotting, editing, and manipulating data in HEC-DSS (USACE 1995) database files. Wurbs et al. (1995) reports an application of an earlier version of WRAP in conjunction with the RESALT model for salinity considerations in evaluation water supply capabilities of reservoir systems. Wurbs applied WRAP model to the Brazos

River Basin in Texas. RESALT is similar to HEC-HMS (Hydrologic Engineering Center's Reservoir operation simulation software (USACE 2007)) to simulate sequential operation of a reservoir-channel system with a branched network configuration including salinity modeling. Improvement of the salinity modeling is proposed as a future enhancement.

GEOGRAPHIC INFORMATION SYSTEMS IN WATER RESOURCES

Srinivasan and Arnold 1994 developed a modeling system that integrates the Soil and Water Assessment Tool (SWAT) (Arnold 1992) with GRASS, a U.S. Army GIS system (USACE 1988). The modeling system uses GIS as a tool to define modeling parameter (e.g., watershed runoff, stream characteristics, slopes, watershed boundaries, and flow direction) and aggregate inputs for its distributed basin scale model (SWAT). This research demonstrated the effectiveness of using GIS to automate model input to assist with management of runoff, erosion, pesticides, and nutrient movement in large basins.

ArcHydro is a water resources data model applied within geographic information system (GIS) technology to provide a variety of hydrologic solutions (Maidment 2002). ArcHydro generates both raster and vector watersheds map layers based on Digital Elevation Models (DEM). A DEM is a grid in which each cell is assigned the average elevation over the area represented by the cell. ArcHydro also builds sub-watersheds for user-defined points within the system, and allows users to build hydro-networks of rivers and streams from the generated watersheds. ArcHydro offers functionality to assign unique identifiers to system features (HydroID), allowing establishment of relationships between features and data in the database. In addition, ArcHydro provides a data structure (i.e., a standardized template) allowing linkage between hydrologic data and water resources models and synthesis of geospatial and temporal water resources data. This template can be used for something as basic as hydrologic data storage, or for something as complex as executing regional interoperability and data sharing between local and state agencies with joint control over water resources. ArcHydro itself does not offer functionality to model water movement or water quality within the system.

Olivera et al. (2003) highlighted the ability of ArcHydro to facilitate interchange of spatial and temporal hydrologic information among applications. They demonstrated the data interchange between ArcHydro and the Hydrologic Model System (HEC-HMS (USACE 2007)), developed by the U.S. Army Corps of Engineers' Hydrologic Engineering Center in Davis, California, as an example of the hydrologic data integration. Maidment (2002) presented successful applications of ArcHydro concepts in the Guadalupe River Basin, Trinity River Basin, and San Marcos River Basin in Texas. These applications demonstrate drainage systems, and hydrography and hydrologic modeling. The Guadalupe River Basin case study illustrated the development of hydro networks and the relationship between hydro-junctions and system features such as monitoring points, water bodies, and drainage areas.

Shannon et al. (2000) developed a tool that provided a metadata framework for linking GIS coverages with the procedural MODSIM river basin network flow model. GIS was applied to synthesizing spatially-distributed steam-aquifer response coefficients for inclusion into MODSIM for conjunctive management of surface water and groundwater resources in a river basin. Application of the principle of superposition (Bear 1979) allows individual excitation events to be calculated independently and the responses linearly combined. In this case, response of the groundwater system due to external excitations such as pumping, recharge or infiltration at any point in space and time can be expressed as a set of unit coefficients independent of the magnitude of the excitation. The linearity assumption can produce errors when the groundwater flow characteristics as not linear such as for unconfined aquifers with drawdown exceeding 10% of the original saturated thickness, the linearity assumed could lack credibility when large amounts of complex simultaneous events are to be represented. However, in this case, the response coefficients can be recalculated based on the new levels in the aquifer. This tool was applied to the Lower Snake River flow augmentation study by Johnson and Cosgrove (1999), where stream-aquifer interaction in the basin was modeled using MODRSP (Maddock and Lacher 1991)-calculated response functions for each cell on the river reaches cells. Although the groundwater model cell size was relatively coarse ($25Km^2$), the compiled results require an extremely large database that is difficult to edit, maintain and process. Preprocessing of the database is necessary for efficiently running MODSIM using the response coefficients. Proposed future work includes a direct linkage between GIS and MODSIM by importing response functions and extracting river basin topology directly from geo-datasets.

McKinney et al. (1997) developed a prototype GIS-based decision support system for river basin management in ArcView GIS (ESRI, Inc.). The prototype is based on an extension of the concept of decision support system called spatial decision support system (SDSS). The SDSS is an integration of GIS and DSS, as first suggested by Densham and Goodchild (1989). In an SDSS, the system is represented using spatial objects and thematic objects, with the spatial objects representing the real world entities and the thematic objects including the network, attributes, logical and political relations; and models. The prototype system automatically generated a physical node-link system representation based on the spatial relationships of the system features. The system features (nodes) are automatically connected using links that are derived from the spatial relation functions. The user manually modifies the automatically generated network (i.e., adds or deletes nodes and links) to build the final network required for the particular study. A user interface integrated into ArcView allows entry of external information to build the system model. Having all the system features and connections in the network explicitly defined results in a cumbersome representation of the system, making the network dense and difficult to manipulate and explain to those unfamiliar with the model since it appears quite different from the real system. The GUI created for this prototype is a good example of a graphical-spatial interface with fully integration of the model inside a GIS package. The purpose of the research was to develop a water allocation tool. Water was allocated by solving an optimization problem that combines six objectives using user defined weights, subject to constraints on physical, policy and system control requirements. The objectives included in the optimizations are: (1) maximize the satisfaction of water demand, (2) minimize the differences in water shortages, (3) maximize downstream flow in the main river, (4) minimize salt concentrations in the water system, (5) maximize satisfaction of hydropower generation demands, and (6) minimize the amount of water diverted from other basins. The model allocates water based only on the optimization of the pre-defined objectives, and lacks the ability to allocate water according to the prior appropriation doctrine. It also appears to be difficult to implement complex river operations such as exchanges, reservoir accounts and reservoir operations.

STREAM-AQUIFER INTERACTION

The increasing stress on water systems has highlighted the inseparable relationship between surface water and groundwater resources since the development of either groundwater or surface water affects the other (Winter et al. 1998). Therefore, adequate representation of stream-aquifer interaction is a major concern for developing accurate basin scale models, especially in basins where return flows and depletions constitute a significant portion of the surface water flow.

Stream-aquifer interaction is a complex phenomenon to understand and model. Streams can gain water from the groundwater or lose water to groundwater, as illustrated in Figure 2.1. The direction of the flow changes seasonally, temporally and spatially as water levels in both the aquifer and the stream change with respect to each other. Stream can be connected to groundwater through the saturated zone, or disconnected with an unsaturated zone in between, with the former resulting in more rapid responses to changes in the system. As shown by Morgan and Jones (1999), pumping from an aquifer also directly affects the stream-aquifer interface due to the propagation of pumping impacts in all directions in unconfined aquifers. This example showed how surface water is captured spatially within the basin after the groundwater system has achieved equilibrium. Hubbell et al. (1997) studied the temporal effects on surface water discharge prior to the groundwater system achieving a equilibrium state. This study highlights the importance of taking transient response times of groundwater systems into account in long-term water resources planning.

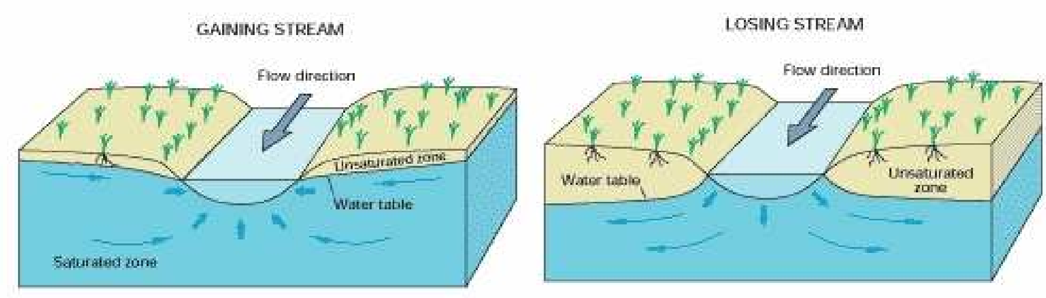

Figure 2.1 – Stream-aquifer interaction [modified from Alley et al. (1999)]

For more than 50 years, researchers have studied stream-aquifer interaction and have developed methodologies to represent it. Analytical solutions approximate groundwater systems with simplified approaches. The parallel drain analogy describes stream-aquifer system interaction as flow between two parallel drains (Maasland 1959).

A popular method based on the Glover (1974) solution is the stream depletion factor (SDF) method (Jenkins 1968), where SDF is a system descriptor with time dimension. The method predicts the volumetric change in streamflow due to recharge or withdrawal of water from the aquifer by merging spatially-varied hydraulic properties, aquifer stress locations, and types of boundaries. Jenkins et al. (1972) calculated SDF values for the LARV, making available hydrologic maps and response coefficient tables to estimate monthly changes in streamflow due to aquifer recharge or withdrawal.

Frevert (1983) estimated subsurface flow to the river using the Dupuit-Forchheimer approximations, such as the segmented model and the segregated model. These methods assume the hydraulic gradient at any point to be equal to the slope of the water table above the point and the equipotential lines to be parallel to each other. The segmented model divides the irrigated area above the alluvial aquifer into three areas parallel to the river segments, and relies on well defined hydrological and agricultural parameters. The segmented model lacks the ability to predict year-to-year changes and peaks in return flows, and is unable to simulate lags between diversions. Since the segregated model calculates evapotranspiration, effective precipitation, and subsurface flow, Frevert (1983) concluded that this method as more flexible in the prediction and timing of peak return flows than the segmented model.

Stream-aquifer interaction has been modeled using approaches that do not rely on hydrological, geological, or agricultural parameters. The Nash Model utilizes a general response function based on a model consisting of a number of equivalent linear reservoirs (Nash 1968). The formulation does not rely on hydro-geologic parameters, but instead needs the estimation of theoretical parameters during the calibration process. The model uses evapotranspiration, effective precipitation, and deep percolation for all irrigation systems in one alluvial valley and uses a convolution process to calculate the return flows. The Nash Model seems to accurately predict year-to-year fluctuations, varying the annual carryover effect through the calibration process. The multiple correlation model is a statistical model that estimates return flow based on a regression approach, optimizing parameters to minimize the error between the predicted and the measured data (Frevert 1983). This model uses hydrological, climatological (e.g., temperature, sunshine factor, and precipitation) and agricultural conditions as input variables. Existing stochastic models for analyzing flow in heterogeneous media (Li and McLaughlin 1991) are either based on assumptions that are too restrictive to be applicable at real-world field sites, or computationally cumbersome and expensive to be practically implemented at sites of realistic sizes.

Hydrologic watershed modeling studies have addressed the issue of modeling stream-aquifer interaction by estimating the return flows from groundwater as a portion of the surface flow in the stream at the watershed outlet. The “abcd” model is a nonlinear watershed model the produces streamflow based on precipitation and potential evapotranspiration as model inputs (Thomas 1981). The model internally accounts for groundwater storage, soil moisture storage, direct runoff, and groundwater outflow to the stream channel. The model parameters *a*, *b*, *c*, and *d* have physical interpretation, where parameter *a* is the propensity of runoff before the soil is completely saturated, parameter *b* is the sum of actual evapotranspiration and soil moisture, *c* is the fraction of streamflow arising from groundwater discharge in a given month, and the reciprocal of the parameter *d* is associated with the average groundwater residence time.

With similar but more elaborated approach, the precipitation-runoff modeling system (PRMS) is a deterministic, physical-process-modeling system designed to analyze the effects of varying climatological and land use conditions on streamflow, sediment yield and general basin hydrology (Leavesley et al. 1983). Risley (1994) calibrated the PRMS model for 11 small drainage basins in Oregon, with each basin conceptualized as an interconnected series of reservoirs whose collective output produces the total hydrologic response. These reservoirs include interception storage in vegetation, impervious-area storage on the surface, storage in the root zone, subsurface storage between the surface of the basin and the water table, and groundwater storage. Model calibration consists of estimating parameter values to minimize the error between the observed and predicted basin-outlet flows. Risley (1994) uses all the studied drainage areas at the same time for calibration to provide regionalized parameters that assist in hydrologic simulation of other gauged and ungauged basins in that region. Defining the parameters controlling the subsurface and groundwater contribution rates is difficult with use of any measured, physical basin data. These parameters are usually estimated using optimization tools (Rosenbrock 1960) and have been found to be the most sensitive of the calibration parameters (Allen and Antonius 1993). Therefore, the prediction of return flows using these methods is not expected to be accurate since there are many other factors that control the physical process that will be included in these calibration parameters as results of the optimization process. In addition, this method lacks the ability to predict spatially varied stream-aquifer interaction within the basin.

CALVIN (CALifornia Value Integrated Network Model) is a network-flow based economic-engineering optimization model developed at the University of California, Davis (Howitt 1999, Jenkins and Calfed Bay-Delta Program 2001). This model uses a simplified representation of the aquifer in order to apply optimization to the conjunctive use of surface and groundwater resources. Groundwater basins are represented as lumped reservoirs with a fixed capacity, and are treated in the same manner as surface reservoirs (Jenkins and Calfed Bay-Delta Program 2001). The groundwater reservoirs dynamically interact with the surface system driving the optimization process.

MODFLOW, the USGS Modular Three-Dimensional Ground-Water Flow Model (McDonald and Harbaugh 1988), is a widely used groundwater finite difference model to simulate groundwater elevations or piezometric surfaces and groundwater flow. The model requires the creation of cells to represent the modeling space and a detailed description of the system hydraulics. Some of the required model data includes hydraulic conductivity, transmissivity, specific yield, boundary conditions (i.e., locations of impermeable and constant head boundaries), and stresses such as pumping wells, recharge from precipitation and irrigation, rivers, and drains. MODFLOW is organized into modules, with each module including packages that control specific aspects of the simulation. The MODFLOW-streamflow routing package is used to simulate stream-aquifer interaction in intermittent streams by calculating stream/canal stages using Manning's equation, known stage values, or a values table to calculate inflow and outflow to the aquifer from the stream by limiting aquifer recharge to the water available in the stream. The package allows merging of stream branches and simulation of diversions.

As discussed previously, stream-aquifer interactions can be represented by "response functions" that describe the relative response of the aquifer system at a given location due to a unit change in the stress (recharge/pumping) at another location. Because the response is expressed in relative terms, it may be scaled to any magnitude of stress desired. The functions may express transient or steady-state response of the system to the stress. The development and use of response functions requires that the response is proportional to the magnitude of the stress; consequently, the governing equations must be approximately linear. Similar or identical concepts have been called discrete kernels (Morel-Seytoux 1975), influence coefficients (Illangasekare and Morel-Seytoux 1982), algebraic technologic functions (Maddock 1972) and drawdown simulations (Anderson and

Woessner 1992). The assumption of linearity of the governing equations is the major drawback in the application of response function methodology.

Numerical models such as MODFLOW or MODRSP (Maddock and Lacher 1991), which is a modified version of MODFLOW, generates response functions by applying MODFLOW to stress all individual grid cells and determine the resulting unit response at the river cells. This method is extremely demanding in terms of data requirements, with most of the inputs variable in space and some variable in time. Some of the inputs include, but are not limited to, stream and reservoirs cells definition with information about water elevation and parameters such as hydraulic conductivity and conductance (as a function of the stream bed materials and physical characteristics); aquifer transmissivity, groundwater system boundaries, and excitation cell locations such as pumping wells, aquifer recharge, reservoir seepage, or channel losses. Response coefficients for river reaches can be generated by combining individual results in all cells in the reach for incorporation of response functions into the surface water models such as MODSIM.

AQUATOOL, a decision support system developed by the DIHMA of the Polytechnic University of Valencia (Andreu et al. 1996), uses an approach similar to MODSIM for simulating systems using optimization techniques. AQUATOOL implements a conjunctive groundwater and surface water modeling in the water system simulation. The aquifer is simulated using several approaches, ranging from simplified reservoir/pumping only to elaborated distributed parameter model. The groundwater module is integrated with the tool network flow solver using an iterative procedure, where the network solution is used in the groundwater module providing information for the next iteration of the network flow solution. Paredes-Arquiola et al. (2004) implemented GESCAL, an interface that couples QUAL2E and the AQUATOOL modules, to simulate several water quality constituents in rivers and reservoirs. GESCAL is applied to observe water quality changes from various operational scenarios and their effect on planning future treatment plant facilities.

The Kansas Hydrologic-Institutional Model (HIM) (Burkhalter 1997), which was specifically developed for purposes of the Supreme Court Kansas v. Colorado case regarding the violation of the Arkansas River compact. The model is applied to estimating flow in the Arkansas River that would have occurred in the absence of post-compact well pumping in Colorado. HIM uses a mass balance approach to simulate water quantity only, and models the Arkansas River from the downstream end of Pueblo Reservoir to the Colorado-Kansas state border over monthly time steps between the years 1950 and 1994. The model takes into account 25 water users and eight reservoirs and accounts for some operational characteristics such as the prior appropriation doctrine, the winter water storage program, and trans-mountain water. The estimated streamflow is then used to determine whether Colorado has met its obligation under Article IV-D of the compact to ensure that any new water development in Colorado has not materially depleted Arkansas River flow at the Colorado-Kansas border. The model has been modified and updated several times over the years by modelers in both Colorado and Kansas. More recently, the courts have stipulated that the HIM model requires more accurate determinations of crop consumptive use as calculated by the Penman Montieth Method using updated and improved data sets, with the resultant consumptive use estimates then input into the HIM Model. The HIM Model is not accurate on either annual basis or short-term basis, as stated by the Special

Master in the Kansas v. Colorado case. The Special Master adopted the Colorado proposal to apply the model over a ten-year period in order to average out errors. It is believed that the primary source of error is the lack of an accurate stream-aquifer modeling component. In contrast, the methodology presented in this research includes detailed regional scale models that provide a strong basis for accurately representing the stream-aquifer interaction.

The Integrated Ground water-Surface water Model (IGSM2), developed by the State of California Water Resources Department Modeling Support Branch of the Bay-Delta Office, simulates groundwater flow, surface water flow, and surface-groundwater interaction (DWR 2003a, 2003b). The model simulates groundwater elevations and horizontal and vertical groundwater flow in a multi-layer aquifer system using the Galerkin finite element method to solve the non-linear conservation equation. IGMS2 uses a similar approach to the MODFLOW streamflow-routing package to model surface water flow and stream-aquifer interaction. Four land use categories are used to dictate the evaporation, surface runoff, and infiltration characteristics as well as agricultural and urban water demands. Direct runoff is updated using a rainfall-runoff relation developed by the National Resources Conservation Service based on a curve number (*CN*) which indicates runoff potential. Diversion water and pumping water is distributed to meet agricultural and urban water requirements. IGSM2 was applied to the California Central Valley Project Improvement Act studies and many regional applications throughout California and the United States. For example, the CALFED Program for developing and implementing a long-term comprehensive plan to restore ecological health and improve water management for beneficial uses in the California Bay-Delta System, has used IGSM2 for integrated storage investigations. The model lacks a powerful water allocation algorithm, and assumes prior knowledge of diversion and bypass water for stream modeling. The amount of return flow from irrigation and urban water use is computed as a pre-specified fraction of the water applied to agricultural and urban lands.

ARTIFICIAL NEURAL NETWORKS

Artificial neural networks (ANN) are "massively parallel interconnected networks of simple elements and their hierarchical organizations which are intended to interact with the objects of the real world in the same way as biological nervous systems do" (Kirby 1993), or simply a "system of interconnected computational units" (Kirby 1993). A simple neural network (NN) consists of an input layer, a hidden layer and an output layer. These layers have a number of nodes or neurons. Input nodes receive data from sources external to the network and send them to the hidden nodes, in turn the hidden nodes send and receive data only from other nodes in the network, and output nodes receive and produce data generated by the network which goes out of the system (Govindaraju and Rao 2000).

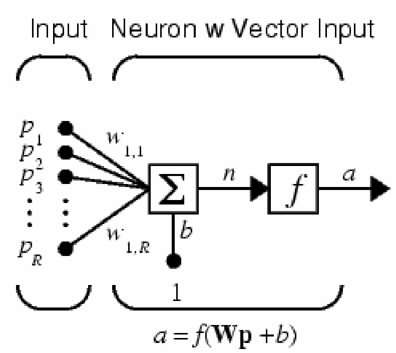

Figure 2.2 – Simple neuron diagram

The NN basic information-processing unit is the *neuron* (as descried on Haykin 1994). The neuron consists of: (1) a set of connecting links, each link characterized with a weight (*w)* or strength, (2) a *combiner* that combines all the signals multiplied by their corresponding weights and (3) an *activation function* for limiting the amplitude of the output. Usually the neuron activation input (*n)* is combined with a *bias* term (*b*). Figure 2.2 shows representation of a simple neuron with bias (Hagan et al. 1996). p_i is the *i* neural net input and *R* is the number of elements in the input vector. Activation functions transfer the neuron activation inputs (*n*) to the next layer; the most common are linear (*purelin*), hyperbolic tangent sigmoid transfer function (*tansig*), log-sigmoid (*logsig*), triangular basis and radial basis (*radbas*).

Backpropagation Neural Networks

The NNs in this group are characterized by having a common training procedure. The term *backpropagation* refers to the manner in which the gradient is computed for nonlinear multilayer networks. Standard backpropagation is a gradient descent algorithm, as is the Widrow-Hoff learning rule (Rumelhart et al. 1986), in which the network weights are moved along the negative of the gradient of the performance function.

Feed-Forward NN

This type of network is based on the *perceptron* concept introduced by Rosenblatt (1962), which projects the input nodes onto hidden layers and output nodes exclusively, with no connections in the opposite direction. This ANN receives weighted inputs from nodes in the input layer, and with each succeeding layer receiving weighted inputs only from the preceding layer. Figure 2.3 shows a diagram with an example of a two layer feed-forward NN. The example NN has two input variables (p_i), and four hidden neurons in the first layer (each one with a bias) and three hidden neurons in the second layer. $IW_{1,1}$ = input weights matrix for the first layer with source in the first layer. $LW_{2,1}$ = the layer weights matrix with source in layer 1 and destination layer 2. Bias (b_i), net input (n_i), and output (a_i) have a superscript *i* to say that they are associated with the network layer *i*. The transfer functions in Figure 2.3 example are tangent sigmoid for the first layer and linear in the second layer.

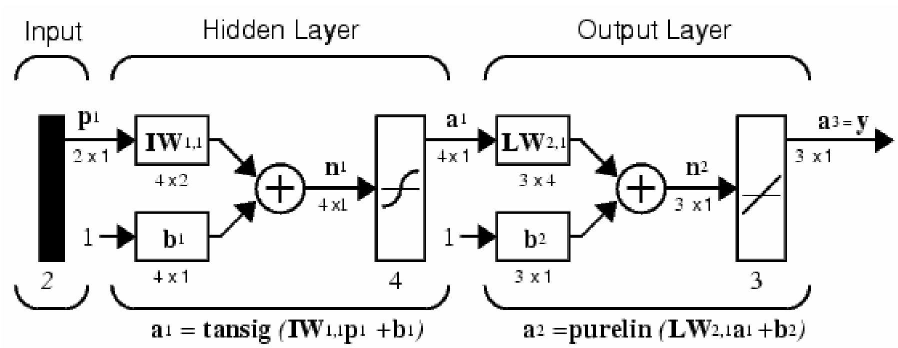

Figure 2.3 – Feed-forward neural network example

Elman NN

This network feeds back to nodes in the input layer the output generated by the input layer nodes (Elman 1990). This recurrent connection allows the Elman network to both detect and generate time-varying patterns. Figure 2.4 shows a diagram of the network structure, where the delay **D** uses first layer outputs from the previous time step (*k-1*). This network stores information for future reference, being able to learn temporal as well as spatial patterns. This network differs from the Jordan neural network (Jordan 1990) in having recurrence on the layer output it self rather than on the network output (a_2). The Jordan NN uses as "internal" input from the previous time step outputs.

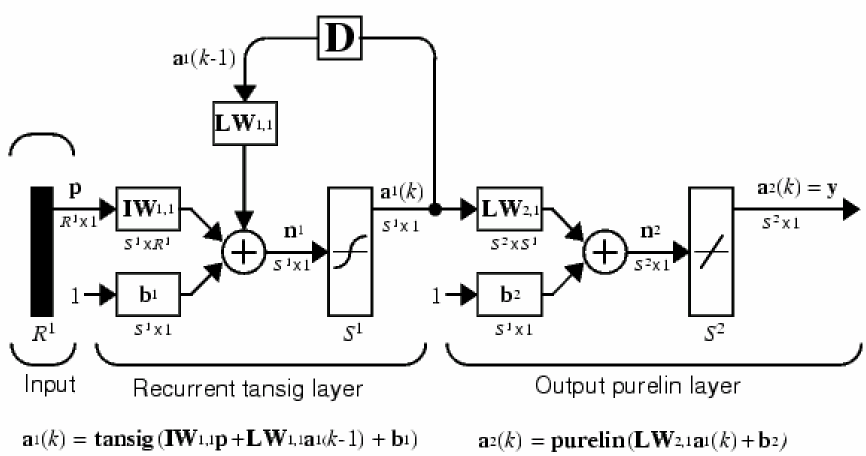

Figure 2.4 – Elman NN structure diagram

Cascade-Correlation-Forward Networks

This network structure and training algorithm is introduced by Fahlman and Lebiere (1990). In this type of feed-forward network, the first layer has weights coming from the input. Each subsequent layer has weights coming from the input and all previous layers. All layers have biases. The last layer is the network output. The training algorithm adds hidden neurons to a multi-layer structure and trains the new unit individually, claiming to speed up the learning process.

Radial Basis Networks

This type of network includes two layers: a radial basis layer and a linear layer (Haykin 1994;Chen et al. 1991). The radial basis layer is characterized by using a radial transfer function *radbas* defined as:

$$radbas(n) = e^{-n^2}$$

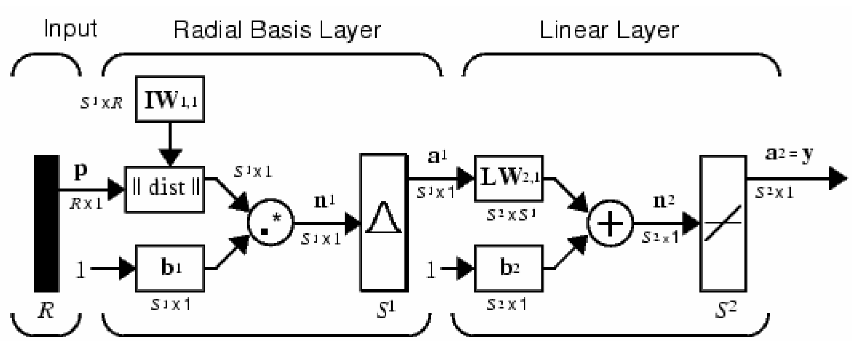

Figure 2.5 – Radial Basis Network structure diagram

In Figure 2.5, R = the number of elements in the input vector, S^i= number of neurons in layer i. $\| Dist \|$ = the distances between the input vector and vectors i in rows of the input weight matrix ($IW_{1,1}$). The bias b_1 elements, in the first layer, are multiplied time the elements of the $\| Dist \|$ vector (element-by-element multiplication). The bias allows the sensitivity of the *radbas* neuron to be adjusted.

Generalized Regression Network

This special type of radial basis neural network, introduced by Specht (1991), has a special linear layer (second layer). The outputs from the first layer (a^1 on Figure 2.5) are combined with the row of the layer weights ($LW_{2,1}$) using a dot product, resulting in a vector with S^2 elements.

Application of ANN in Water Resources

Several successful applications of ANN in water-related problems are found in the literature. Particularly in the groundwater modeling area, Maskey et al. (2000) trained a network to approximate groundwater flow and transport as predicted by the models MODFLOW and MODPATH. The ANN training and validation showed its ability to predict modeled-site clean up time and clean up cost to a reasonable accuracy. Results showed a better performance in predicting smaller clean up times. For a sub-group of predictions consisting of the smallest 50 % of the predictions, the ANN was able to predict the model output with coefficients of determination ranging from 0.95 to 0.97. An advantage reported in this study is that the ANN reduces the computation time in simulation processes compared with traditional (physically-based) models. An ANN model is much faster than the physically-based model that it approximates, facilitating the application of optimization routines to the problem. Once an ANN is suitably trained to imitate a particular aquifer system, it can be applied for further use in optimal management of the system (Das and Datta 2001). Rogers (1992) and Rogers (1994) employed an ANN, which was trained by a solute transport model, to perform successful optimization studies in groundwater remediation. For training of an ANN for a groundwater system, it is necessary to use several groundwater responses corresponding to a variety of aquifer stress scenarios.

Darsono and Labadie (2007) presented a good example of machine learning application to optimal real-time regulation of flows and in-line combined sewer system. This study trains a Jordan neural network (Jordan 1990) on the optimal policies generated by an dynamic optimal control module, demonstrating the advantages of using recurrent type NNs in time-varying patterns process.

The role of ANNs in various branches of hydrology was examined by Govindaraju and Rao (2000). It was found that ANNs are robust tools for modeling many nonlinear hydrologic processes such as rainfall-runoff, stream flow, groundwater management, water quality simulation, and precipitation. After appropriate training, they are able to generate satisfactory results for many prediction problems in hydrology. Jia and Culver (2003) applied the bootstrap technique to train an ANN for synthetic flow generation with a small data sample. The advantages of this technique are the ability to estimate the expected value of the prediction and the interval of confidence and to guide the ANN selection process. Jia and Culver (2003) found it useful that the technique does not require separate available data in training and testing datasets, thereby avoiding the issue of selecting the optimal size for these datasets. Use of a maintenance of variance extensions (MOVEs) model aided the ANN in the flow generation when close to the training boundaries. Performance of the bootstrapped ANN model was successfully tested on the Buck Mountain Run case study.

Bowers and Shedrow (2000) used an ANN to predict the water quality variables in Mill Creek, a tributary of the Savannah River in South Carolina. A feed-forward ANN was trained to predict total suspended solids, total dissolved solids and total solids using precipitation, flow rates and turbidity measurements. Precipitation data used in the study was a USGS rain gauge in the studied watershed. The water quality training and validation dataset is composed of data measured during a 21-month period close to the Mill Creek watershed outlet. A coefficient of determination of 0.96 is calculated between the measured and predicted total suspended solids when the ANN is prediction only total suspended solids. On the other hand, when predicting total suspended solids, total dissolved solids, and total solids at the same time the coefficients of determination are 0.85, 0.94, and 0.95 respectively. The results showed a better performance of the ANN in predicting only total suspended solids.

Sandhu et al. (1999) develop an ANN to model the flow-salinity relationship with application to the Sacramento-San Joaquin Delta in California. The ANN was trained using historical measurements and the Delta Simulation Model 2 (DSM2), a 1-dimensional hydrodynamic and water quality model capable of simulating flow, stage, and water quality throughout the Delta. In this study, the explanatory variables for the ANN were river flows, canals gate positions, and diversions, including exports. Sandhu et al. (1999) explored different time steps to group the inputs variables and the concept of memory, including previous time steps values as inputs for the explanatory variables. They found that in using daily time steps there was less loss of information than for coarser time steps. In addition, they found that memory played an important role in the ANN predicted v. observed results showing significant improvements in the predictions when previous time step values where introduced. Unfortunately, limited statistical analysis of the errors was found in the literature reviewed. This ANN was intended to bring the detailed DSM2 water quality modeling results into CALSIM. Wilbur and Munevar (2001) reported a successful integration of the trained ANN into the CALSIM linear optimization solver by using a linearized constraint from the ANN salinity prediction. In one of the cases, the integral CALSIM-ANN Model allowed determination of reservoir releases to meet salinity requirements in the system.

Suen and Eheart (2003) applied ANN to predict Nitrate concentration in the Upper Sangamon River in Illinois, a typical Midwestern river. The explanatory variables used in this research were weekly cumulative precipitations, daily highest temperatures in three stations, daily streamflows, and the Julian date. The target values are daily Nitrate concentrations at a gauged point in the system. ANNs were compared with traditional methods such as multiple regression analysis (MRA) and the SWAT model, a mechanistic soil and water assessment tool (Arnold et al. 1996). In addition, the performance of radial basis neural nets and backpropagation neural nets was compared, showing preference for radial basis neural nets (RBNN)-based on production of more robust results and faster training. Prediction performance was analyzed based on accurately determining concentrations above or below the Nitrate concentration standard in the river. The false-negative and false-positive frequencies are used to estimate overall accuracy. The best overall accuracy corresponding to the RBNN was calculated between 78% and 83% for two different training scenarios. The overall accuracy was improved (86-89%) when training the ANN to predict a binary output.

Parkin et al. (2007) uses SHETRAN, an integrated watershed modeling system numerical model, to develop an ANN-based model to predict effects of groundwater abstractions in river systems in The United Kingdom. SHETRAN is a physically-based distributed modeling system for simulating water flow, sediment and contaminant transport in river basins (Ewen et al. 2000). It was chosen for this study due to its capabilities for representing integrated groundwater–surface water systems. SHETRAN provides the time-series and spatial variations in river flow depletion. The depletion curves are fitted from the SHETRAN simulations, thereby reducing the number of variables to predict. Two ANNs were applied in this study, with the first producing a binary output indicating wet conditions at the well, and the second generating model output to represent the depletion curve. The model predictions were tested with a unique field pumping experiment data set in the Winterbourne stream, UK that showed a predicted depletion curve with similar shape to the one found in the field experiment; Parkin et al. (2007) concludes that the similarity in the depletion curves from model with different parameters show the applicability of the model for realistic conditions modeling. This study demonstrates the successful application of a hybrid, numerical model-ANN, approach for modeling stream-aquifer interactions, and its potential for modeling more complex hydrological systems.

WATER QUALITY MODELING

Water quality relates to physical, chemical and biological characteristics of water. Salinity is a measure of the amount of salt dissolved in the water. Salts are substances such as “table salt” (sodium chloride, NaCl), limestone (calcium carbonate, CaCO3) and many others. They are picked up by the water as it runs over and through the rocks and soils of the basin. Low levels of these salts are vital to the growth of aquatic plants and animals but high levels can cause problems for aquatic life and for human uses such as crop irrigation. Modeling groundwater quality issues in irrigated river valleys has interested researchers for many years (Darton 1906; Austin and Colorado. Dept. of Public Health and Environment 1997; Bossong et al. 2000; Freiwald et al. 1988; Watts et al. 1992), and specifically salinity issues in irrigated land with significant reduction in crop yield (Miles et al. 1977; Gates et al. 2002).

Ground Water Quality in the Arkansas Valley

Gates et al. (2002) applied the GMS software package (Brigham Young University 1999) to model steady state groundwater flow and salt transport to a portion of the LARV in Colorado. GMS integrates MODFLOW for groundwater flow calculation and MT3DMS for conservative salt transport with a GIS-based interface for ease of defining the extensive spatial database requirements. The MODFLOW-MT3DMS model was developed to analyze and predict water table elevations and salinity and to simulate the interaction between the shallow aquifer, the river, and the irrigation-drainage system. This model includes a module to simulate the water quantity and quality in the unsaturated zone, and an improved module for drainage system improvements modeling. The model was calibrated based on extensive and detailed data collection effort. The finite difference model was applied using cells representing 6.25 ha, corresponding to roughly half the average field size in the region. The initially developed steady-state model has been further calibrated as a transient model over a 133 week period encompassing three consecutive irrigations seasons of data gathering from 1999 to 2001. The transient model provides an invaluable resource for understanding quantity and quality components of the stream-aquifer interaction and evaluating salinity control strategies (Burkhalter and Gates 2005, 2006).

Data collection has continued for six years, and in the near future it is expected that the transient model will be applied from 1999 to 2004. In addition, in the past five years the data gathering has been extended to an additional region downstream of the earlier modeled area. The same modeling schema will be applied to the downstream area. Some of the most outstanding features of the current transient finite difference model are: (1) an unsaturated zone model for water quantity and quality, (2) detailed evapo-transpiration calculation based on historical crop records and its dependency on the soil salinity, and (3) a module to include subsurface drainage modeling. The salinity and waterlogging control strategies that have been evaluated include: increases in well pumping rates, irrigation recharge reductions, seepage reductions, subsurface drainage, and combined strategies. Preliminary findings showed the most significant regional benefits by reducing excess recharge by increasing irrigation efficiency.

In-Stream Water Quality in the Arkansas Valley

Cain et al. (1987) studied the regression relationships of specific conductance to streamflow and major-ion concentrations for the surface water systems and groundwater systems of the Arkansas River Valley. Coefficients of determination (r^2) were reported that indicated adequate specific conductance predictions using streamflow. Relationships of specific conductance to the specific ions of calcium, magnesium, sodium, bicarbonate, sulfate and chloride concentrations were also developed for both surface and groundwater at various points along the river basin.

Lewis et al. (1998) studied relations between streamflow and specific conductance related to the reservoir operations in the LARV. The study examined the potential of changing the specific conductance and eventually the water use based on streamflow management. An analysis of the historical flows and changes in John Martin Reservoir operation was conducted before and after Pueblo Reservoir was built. Lewis et al. (1998) found seasonal changes in specific conductance due to mixing of seasonally-high specific conductance and seasonally-low specific conductance water in Pueblo Reservoir. The water mixing translated into an overall decrease in the median specific conductance value of the flow downstream of the reservoir. A general increase in the flows rate after Pueblo Reservoir was completed was also found, which was attributed to the winter storage program, increases in storage, and increased trans-mountain water used for irrigation. Downstream of John Martin Reservoir, the study found specific conductance decreasing significantly from September through April with no major changes during May through August.

Aquifer and Stream Water Quality in Colorado

Malone et al. (1979) developed a basin scale, stochastic steady-state model for water quality throughout the Colorado River basin using an existing model, SALT. The SALT model incorporated stochastic analysis by allowing in-stream salinity and the agricultural base leaching factor to be input as random variables. The agricultural base leaching factor represented an empirical value depicting the tons of salt removed from the soil per acre-foot of water flow through the soil matrix. SALT predicted the expected value and the variance for the natural salt load to the river.

Lee et al. (1993) developed a model primarily for economic policy analysis that considered natural flow variability in determining salt concentration. A set of differential equations were developed to describe the flow of total salts in the Colorado River basin. A steady state model was applied to simplify the number of equations required for the model, and was used to estimate the probability distribution of water quality improvement resulting from specific reductions in salt load or improvements due to different return flow salinity concentrations.

Riley and Jurinak (1979) proposed a concept to explain salt production in a natural watershed. The term *baseline salinity* was used to represent the natural release of salt from a watershed due to hydro-geochemical weathering within a basin. Data showed that the salt mass from a basin is relatively constant, meaning that the natural baseline salinity is relatively constant. Riley and Jurinak (1979) proposed two assumptions to develop the methodology. First, measured data were used to show that, generally, the amount of salt leached from the land is highest when it is first irrigated. It decreases as irrigation continues to what they named an "agricultural base salinity", which is constant. It was proposed that this concept could be applied to any basin once the land has been irrigated for many years, but no exact time frame was provided. Second, once the agricultural base salinity is reached, the salt loading is due only to a combination of the base weathering rate of the soil profile and to the underlying geologic formation. It was further proposed that when both of these assumptions are made, the removal of salt is directly proportional to the quantity of water passing through the soil profile. A relationship between irrigation efficiency and salt loading can be developed using the stated assumptions. Irrigation efficiency is a function of the total volume of water leaching through the soil profile.

Reservoir Water Quality Transport Modeling

Models, such as WQRSS (Smith et al. 1978), HEC-5Q (Hydrologic Engineering Center (U.S.) 1986;Willey et al. 1996), DYRESM (Hamilton and Schladow 1997), and HSPF (Bicknell and National Exposure Research Laboratory (U.S.) 2001), have been developed for water quality basin modeling but have serious limitations. The HEC-5Q (similar to

WQRSS and RESALT) and HSPF models incorporate a one-dimensional longitudinal river model with a one-dimensional vertical reservoir model (only one-dimensional in temperature and water quality and zero dimensional in hydrodynamics). DYRESM is another one dimensional hydrodynamic model with numerical descriptions of phytoplankton production, nutrient cycling, oxygen budget, and particle dynamics. Wells (2000b) introduces CE-QUAL-2E, a two-dimensional (longitudinal-vertical) water quality and hydrodynamic computer simulation model. This model improves previous versions by modeling of the vertical accelerations enhancing river-estuary, lake-river, and reservoir-river modeling. In general, modeling the complexity of the processes in the reservoir for different water quality components requires a large amount of input data. For example CE-QUAL-2E requires: bathymetry, meteorological data, inflows, inflow temperatures, inflow constituent concentrations, tributary inflows, tributary inflow temperatures, tributary inflow constituent concentrations, upstream head elevations, upstream head boundary temperatures, upstream head boundary constituent concentrations, downstream head elevations, downstream head boundary temperatures, downstream head boundary constituent concentrations, outflows, light extinction, withdrawals, vertical profile at dam for specifying initial conditions, longitudinal and vertical profiles specifying initial conditions for each cell, wind sheltering, solar radiation shading, and gate flows/operation.

ANN has been successfully applied to model water quality (eutrophication) in reservoirs around the world. Karul et al. (1999) designs an ANN-based methodology for eutrophication lake management. Karul et al. (2000) trained an ANN to predict Chlorophyll-a concentration variations in four Turkish water bodies as a function of PO4, NO3, alkalinity, suspended solids concentration, pH, water temperature, electrical conductivity, dissolved oxygen, Secchi depth, density of Daphnia species only, and bulk densities of species belonging to Cladocera and Copepoda. In the same line, Walter et al. (2001) predicted Chlorophyll-a in an Australian reservoir. Walter trained the ANN to forecast magnitude of algal biomass in short term (7 days) ahead for early warning and tactical control.