CHAPTER 1

INTRODUCTION, BACKGROUND AND OBJECTIVES

INTRODUCTION

Water systems planning and management include many inseparable elements that make these tasks challenging and complicated. In past years with the abundance and accessibility of computers and software, water systems analysis and decision making have been increasingly accomplished using tools that provide decision makers with valuable information that enhances and facilitates their task. However, when new issues arise, it is often necessary to extend available decision support systems (DSS), if available, or to create new ones to enlarge the knowledge of system behavior, and to aid the decision making process in developing and evaluating management alternatives, including structural rehabilitation, that address the new challenges. Integrated river basin management in which management of water systems is viewed as a part of the broader natural and socio-economic environment is a growing concern for planners, managers and regulators. Effective tools are needed for helping answer questions regarding allocation of scarce resources among competing human activities and for making better decisions on development and sustainable use of water and land resources. Effective river basin management involves not only modeling of the physical river system, but also consideration of the legal-administrative framework and institutional and socio-economic aspects. The work presented herein is an innovative prototype of a spatially distributed river basin scale decision support tool integrating surface and groundwater modeling of water quantity and quality into a river basin management system for effective decision support.

The *River GeoDSS* is developed herein as a spatial-decision support system (SDSS), providing a seamless integration between the spatio-temporal river basin databases and the modeling subsystem. The *River GeoDSS* carries out conjunctive surface and groundwater river basin modeling for water quantity and quality by making use of geo-spatial information and surface and groundwater flow and transport models. The *River GeoDSS* features a water quality module (WQM), allowing integrated modeling of flow quantity and quality, and an artificial neural network (ANN) module for assisting with complex process modeling related to the quantity and quality of natural and irrigation return flows, as well as salt transport through reservoirs. Geographic information systems (GIS) technology is utilized within the *River GeoDSS* to manipulate, process, and store spatio-temporal data. An innovative approach is introduced for accurately modeling the stream-aquifer interactions based on a regional, well-calibrated 3-dimensional groundwater quantity/quality model as an alternative to traditional methods.

Powerful graphical user interfaces (GUIs) and data management tools are incorporated within the *River GeoDSS* to aid users in parameter selection, data entry and processing; ANN training and testing; output display, and management analysis of simulation scenarios. Efficient interfaces are implemented to automate the communication and interaction between models, modules and the underlying spatio-temporal database. The *River GeoDSS* implements MODSIM (Labadie 2006), a state-of-the-art river basin network flow model, as the main modeling engine to carry out the water quantity and quality conjunctive use modeling. MODSIM is selected since it allows not only the water modeling according to physical characteristics and limitations of the system, but also simultaneous modeling of the institutional and administrative elements and regulations. MODSIM is incorporated into the *River GeoDSS* by development of Geo-MODSIM a fully functional version of MODSIM that is incorporated as an extension in the ArcGIS™ geographic information system. The *River GeoDSS* implements a set of customized analysis tools that allow evaluation of "what if" conditions in system operation, irrigation practices, water use, infrastructure improvements, groundwater pumping patterns and water law. The result is a flexible and adaptable tool designed to assist decision makers in comparing and evaluating a wide variety of river basin scale management alternatives.

BACKGROUND

Water quality degradation in agricultural areas can reduce crop yields, thereby threatening the economy and sustainability of rural communities. In addition, water resources are becoming scarcer due to increases in population and the consequential increase in municipal water demands. The expansion of urban populations has generated many municipal water projects focusing on acquiring water rights from agricultural users. Although these projects may be attractive for the depressed economies in the agricultural sector, the outright sale of agricultural water rights to municipalities forecloses future options for the agricultural activity in the river basin. Agricultural water reallocation or changes in agricultural water management practices impact system water users since they change the system dynamics and its equilibrium. Induced changes in irrigation return flow amounts and timing can modify the flow rates and concentration of solutes across the basin, thereby potentially jeopardizing water availability to meet water right entitlements as well as create new environmental and ecological challenges. Therefore, decision making about courses of action requires a broad understanding of the system hydrology, hydraulics, and solute transport, along with environmental, economic, and social aspects. A new focus has arisen on sustainability of agricultural areas that can benefit all users by studying the quantity and quality impacts of changes in water use in these basins. Design of comprehensive solutions for agro-ecological sustainability in irrigated river basins has increased the need to develop powerful support tools that allow addressing complex issues while considering physical, administrative and legal aspects.

The Arkansas River originates in Central Colorado and eventually empties into the Mississippi River. Headwaters of the Arkansas River are located in the 4,267.2-m (14,000-ft) peaks of the Sawatch range of central Colorado, where melting snow is gathered as the primary source of streamflow during October to May. Annual precipitation along the reach of the Arkansas River in Colorado averages less than 254 mm (10 in) east of the mountains, and more than 1016 mm (40 in) per year in the mountain headwaters. The Arkansas River basin in Colorado covers 73,230 km^2 (Figure 1.1). There are several multipurpose systems in the Arkansas River basin. The Fryingpan-Arkansas Project, constructed by the U.S. Bureau of Reclamation (USBR), is a storage and trans-mountain-diversion project that regulates agricultural, municipal and industrial water supplies in Turquoise Reservoir, Twin Lakes Reservoir and Pueblo Reservoir. John Martin Reservoir and the Trinidad Dam and Reservoir Project are primarily flood control projects built by the U.S. Army Corps of Engineers; these projects also regulate irrigation water supplies, and contain recreation pools. The Twin Lakes Project is another storage and trans-mountain-diversion project in the Arkansas Basin, originally developed to serve irrigated lands under the Colorado Canal but, after the sale of the water rights, trans-mountain diversions and storage have become another multipurpose system in the basin. This project, coupled with the Fryingpan Project, provides peak-demand energy generation and additional storage for participants in the Fryingpan Project.

Pueblo Reservoir, located just west of the city of Pueblo, is a multipurpose facility that regulates imported and native water for municipal, agricultural, and industrial use. It contains a joint-use space for flood control in the river from mid April to November. Pueblo Reservoir provides a winter water storage program implemented by the Southeastern Colorado Water Conservancy District and the Colorado Water Resources Division 2, permitting irrigators downstream from Pueblo Reservoir and upstream of John Martin Reservoir to store water in Pueblo Reservoir during the winter months, and to use this water during the crop-growing season. The winter storage program includes off-stream storage and some storage in John Martin Reservoir. Pueblo Reservoir can be used to divide the basin into two sub-basins, each with similar physiographical settings, irrigation practices, and return flow patterns. The Lower Arkansas River Basin in Colorado (Figure 1.1) extends from just below Pueblo Reservoir to the Colorado-Kansas state line, covering about 52,000 km^2 with a main river length of approximately 300 kilometers and containing a total irrigated area of about 1,200 km^2. The Arkansas River is the primary municipal water supply for most of the 170,000 people who live in the five counties that compose the Lower Arkansas River Valley (LARV). The plains agricultural irrigation is based on Arkansas River streamflow diversions to an extensive canal network and on groundwater pumpage.

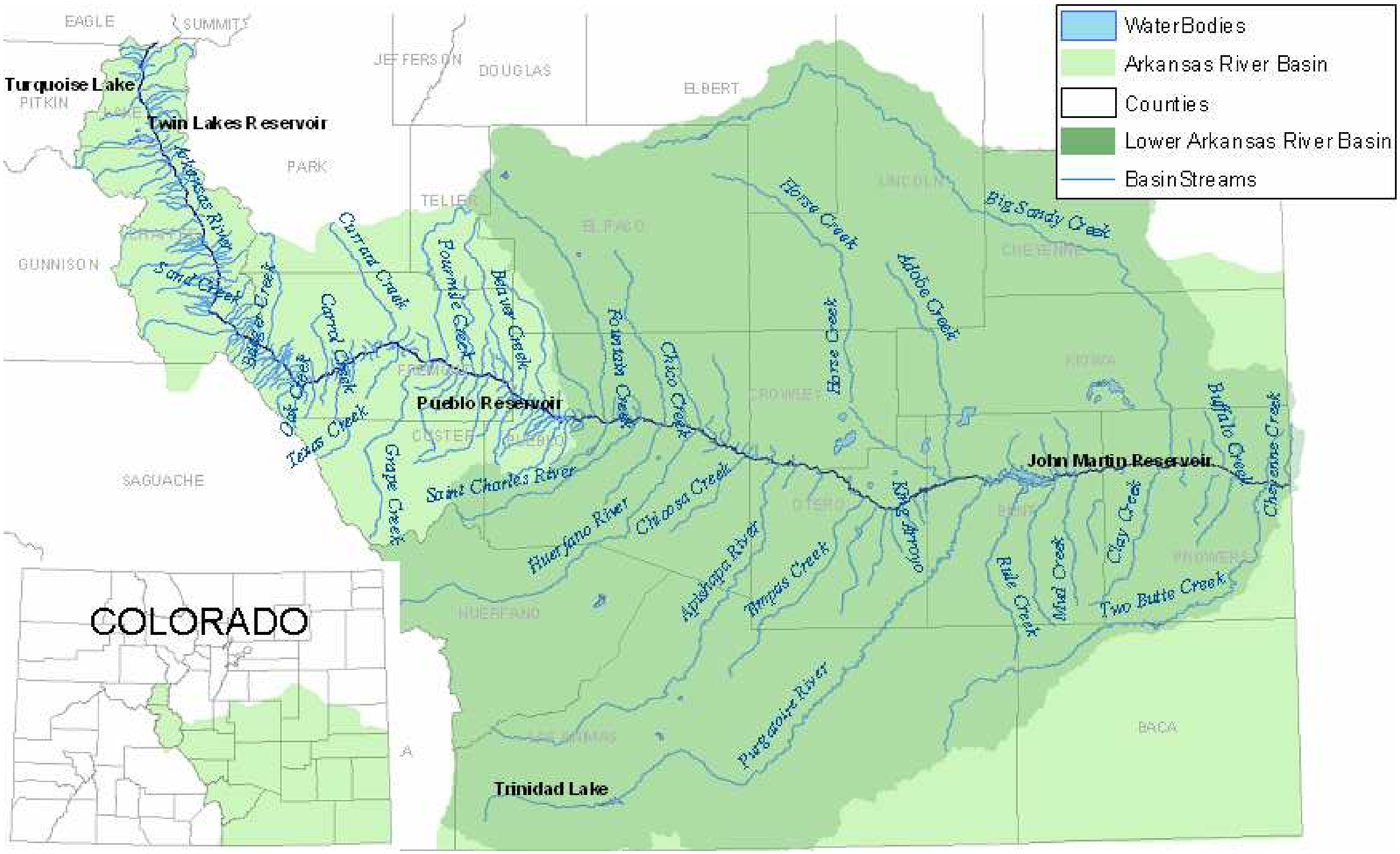

Figure 1.1 – Arkansas River and Lower Arkansas River Basins in Colorado

Waterlogging and salinization is threatening more than 25% of the irrigated land world wide (Tanji 1990; Ghassemi et al. 1995) including the irrigated lands in the LARV. Water in the Arkansas River system is reused several times along the river, where irrigation water infiltrates into the soil, and recharges the alluvial aquifer, with resulting elevated water tables increasing subsurface return flows back to the river. Surface runoff from irrigation enters drains and tributaries that feed the river. These return flows augment natural streamflows for downstream users, especially late in the irrigation season and in fall and winter months. Although users benefit from inefficient water use and return flows, the quality of the water degrades significantly while moving downstream due to dissolution and evaporative concentration. Specifically, salt levels in some stretches of the Lower Arkansas River are approaching one tenth of the concentration found in seawater. Specific conductance, which is directly related to dissolved solids concentration, increases downstream from a median of about 0.5 dS/m (≈340 mg/L) near Pueblo to about 3.9 dS/m (≈3600 mg/L) at Lamar. In fact, the Arkansas River is considered the most saline river of its size in the United States (CDPHE 2002).

High dissolved solids concentrations affect the suitability of water for agricultural, domestic, and industrial uses. Agricultural crop yield losses can occur when dissolved-solids concentrations reach values as low as 700 to 850 mg/L (about 0.95 to 1.2 dS/m). (U S Department of Interior 1994) The secondary maximum contaminant level (SMCL) for dissolved solids in drinking water is 500 mg/L (U S Environmental Protection Agency 1986). The increasing salinity in the Arkansas River in Colorado has been a concern for many years. Konikow and Bredehoeft (1974) developed a flow and salt transport simulation groundwater model for the Arkansas Valley to study the effect of irrigation practices and their relation to the salinity increase. Excess recharge from inefficient irrigation in the basin has caused groundwater levels to rise, creating waterlogging in several areas with the associated problems of salinization (Gates et al. 2002; Burkhalter and Gates 2005; Burkhalter and Gates 2006). Salinization in the soils is demonstrated to be a major factor in reducing crop yields (Gafni and Zohar 2001; Mikati 1997; Patel et al. 2002; Rogers 2002). Based on field data collected between 2002 and 2005, Mueller and Gates (2008) estimated average total dissolved solids (TDS) loadings to the river in an reach upstream of John Martin Reservoir of 8,383 (kg/day)/km and in a reach downstream of John Martin Reservoir of 11,183 (kg/day)/km.

In addition to problems of increased salinity, the Lower Arkansas River is registering selenium (Se) contamination that could threaten the health and safety of humans, animals and aquatic life (Gates et al. 2008). All segments of the Lower Arkansas River are designated as "water quality limited" with respect to Se or/and Fe that have been placed on the current Clean Water Act 303(d) list for TMDL development. Mueller and Gates (2008) investigated and estimated the selenium contamination induced in part by agricultural irrigation practices in a portion of the Arkansas Valley during the period between 2003 and 2005. The average non-point source Se contamination loading to the study area was estimated as 0.038 (kg/day)/km.

Increase in population in cities along the Colorado Front Range has generated a desperate search for new sources of municipal water. The LARV has been targeted by cities such as Colorado Springs, Pueblo, and Aurora as a possible source of water. Many of the proposed options include buying or leasing water from agricultural users, changing points of diversion, and reusing treated waste water from the cities for agriculture. If no actions or provisions are taken promptly, these factors together threaten to permanently harm the already debilitated LARV economy.

High water tables under fallow and naturally-vegetated fields contribute to non-beneficial evapo-transpiration via upflux from the water table through the unsaturated zone. Lower water tables are expected to reduce this water loss from the system (Hallberg et al. 2008).

The LARV in Colorado has been subject to strict regulations in groundwater pumping due to enforcement of court-ordered reparations as a result of lawsuits over violation of the interstate (Kansas-Colorado) river compact caused by post-compact well pumping in Colorado. Kansas claimed that the post-compact well pumping caused additional depletions in the river, diminishing the amounts that were entitled to Kansas in the compact. Therefore, pumping and any other activity that potentially change the pre-compact return flows should be carefully analyzed under the Arkansas River compact.

The Clean Water Act of 1970 and the Federal Water Pollution Act of 1972 were established to unify courses of actions that recognize the important inseparability of water quantity and quality in all water systems. However, many water systems are not managed and regulated to take into account the interaction of water quantity and quality. The State of Colorado is an example of this situation where state policies often divorce the issues of water quality and water quantity. For this reason, agencies such as the Colorado Division of Water Resources, the Colorado Water Quality Control Division, the USGS, the USBR, Water Conservancy Districts, and other decision making entities lack the necessary modeling tools needed to help understand the combined quantity and quality facets of the system. For example, the Supreme Court Kansas v. Colorado case (No 105, 1985) only addresses volumes of water, although the quality of the water could play an important role in the future. This was demonstrated in the case of the Colorado River flow that reaches Mexico (Minute No. 242 of the International Boundary and Water Commission dated August 30, 1973). Integration of water quality and quantity in river basin modeling is not the most common practice. Some models focus on extremely detailed water quantity modeling [e.g., IGSM2 (DWR 2003a, 2003b)], while others concentrate on water quality modeling [e.g., CE-QUAL-W2 (Wells 2000a)]. Dai and Labadie (2001) attempted to integrate water quantity and quality modeling in the Arkansas River basin, but water allocation solutions based on optimizing improvements in water quality (Dai and Labadie 2001; McKinney et al. 1997) would be difficult to implement because of the need to relax the rigorous water laws that dictate water allocation. Water quality needs to be modeled based on viable operational scenarios where water law and river compacts are enforced.

In many cases, analysis of stream-aquifer interaction has been excessively simplified due to the lack of extensive field data. For example, in the Kansas Hydrologic-Institutional Model (HIM) (Burkhalter 1997) applied to the LARV, the groundwater modeling has been performed with sparse field data, thereby limiting the ability of the model to accurately represent basic conditions. Dai and Labadie (2001) used a simplified approach to model groundwater movement and a simplistic method to represent the unsaturated zone. Methods for basin-scale groundwater modeling, especially analytical approaches, rely upon a number of conceptual simplifications, increasing the uncertainty and inaccuracy of the results. Simplifications are often applied to geometry, and to aquifer physical characteristics, for example, such as homogeneity, isotropy, time invariance, and infinite (semi-infinite) aquifer extent. Analytical approaches cannot be applied to groundwater basins with complex boundary conditions and can only approximate the groundwater flow process [e.g., use of Dupuit-Forchheimer assumptions (Dupuit 1863; Forchheimer 1886)]. The primary disadvantage of analytical approaches is that they are not linked to the spatial and physical heterogeneity of the aquifer porous media. In contrast, numerical methods are based on space and time discretization to represent the heterogeneous physical system. However, finite element and finite difference groundwater modeling methods are not efficient when applied over large areas such as an entire river basin. Extensive areas require large numbers of computational elements to accurately represent the system, consuming extensive computer resources. Collecting the necessary data in the field to implement detailed groundwater models such as MODFLOW (McDonald and Harbaugh 1988) and the Integrated Groundwater-Surface water Model 2 (IGMS2) (DWR 2003a, 2003b), and mass transport models like MT3DMS (Xheng et al. 1999), to accurately model a large river basin would be challenging and ambitious. Although, these models can provide more accurate stream-aquifer representation, they lack a powerful surface water module to satisfactorily represent the conjunctive use of water. Sophocleous (1995) compared MODFLOW and the SDF method (Jenkins 1968), which showed considerable discrepancies between the two approaches in representing a real stream-aquifer system. These results were corroborated by Fredericks et al. (1998), who found significant differences using groundwater response coefficients developed from the SDF method compared to using a finite difference groundwater model. There is a need for an alternative methodology that allows accurate basin scale stream-aquifer interaction modeling based on effective field data and detailed groundwater modeling at reasonable computational expense.

Decision making in a river basin system requires assistance from tools that provide an adequate balance between practicality and accurate abstraction of the system. Possibly the greatest challenge when designing a new river basin-scale modeling tool is to understand and overcome the limitations in data collection, availability, and cost. For instance, implementation of a detailed water quality model such as CE-QUAL-W2, a distributed parameter groundwater flow and transport model such as MODFLOW-MT3DMS, or a model within the IGSM2 framework requires extensive and expensive data gathering to accurately calibrate and apply them to a large river basin. Based on current real-world needs, there is an apparent demand for a methodology that provides affordable basin scale tools based on limited but well-conceived field data. The powerful capabilities of geographical information systems, combined with the latest computer programming technology, makes it feasible to conceive an integrated, user-friendly and flexible system achieving a remarkable degree of detail and accuracy in river basin modeling.

The complexity of decision making in river basins encompassing quantity and quality aspects of conjunctive surface water and groundwater use, water law, social groups' interests, and economics requires tools capable of addressing these issues. Although, individual tools help, success derived from combining these tools is becoming increasingly evident. The Yakima River Basin decision support system is a good example of the grouping of tools for enhanced comprehensive studies (McKinney et al. 1997), where the advantages of the concept of SDSS were demonstrated. New developments in SDSSs for evaluating alternatives and quantifying long-term impacts and the potential harm of marked changes in water use, system operations, irrigation practices and infrastructure should effectively blend tools in a geo-referenced graphical user interface and should be spatio-temporal database centered. Emerging technologies such as the .NET framework facilitate the integration of models and the GIS environment, allowing seamless interaction between the internal objects of the DSS components and the construction of new modules for specific modeling tasks. A comprehensive SDSS will facilitate the decision making process and provide better understanding of the system. Initial efforts need to be focused on developing a conjunctive surface and groundwater quantity and quality modeling system that encompasses operational, administrative, and institutional issues designed specifically for river basin scales.

OBJECTIVES

Throughout the literature reviewed (Chapter 2), it is possible to identify the scarcity of solutions that bring together both water quality and quantity in a river basin with seamless integration of models in a spatial-temporal data centered fashion. Deficiencies in adequate stream-aquifer representation at the basin scale are revealed. The most common methods are inefficient for large-scale modeling and most of the studies lack the necessary field data for reliable model calibration and testing. These key elements in basin-scale modeling require improvement and special attention to new developments.

The overall goal of this research is to develop a *River GeoDSS* prototype, a generalized basin-scale spatial decision support system for river basin management alternative screening and evaluation. The *River GeoDSS* is conceived as a geo-spatio-temporal database centered system, employing state-of-the-art modeling/computational tools such as

MODSIM, MODFLOW, MT3DMS, artificial neural networks, GIS, and .NET technology to encompass extensive data processing, modeling and DSS customization. By employing digital information, GIS and automated tools for models interaction, *River GeoDSS* can model water resource systems with an unprecedented degree of detail that can be easily managed and utilized for effective decision making.

The *River GeoDSS* development has the subsequent objectives and procedures:

1. Create a set of core tools and interfaces for seamless data and model interaction inside the GIS environment, including data preparation and results presentation, display and analysis.
    1.1. Couple MODSIM, MODFLOW, and MT3DMS with the GIS environment (ArcGIS™), geo-referencing the models' objects and making them available through the GIS interface.
    1.2. Include and combine hydraulic, hydrologic, administrative, operational, and institutional aspects in the modeling system.
2. Develop the *River GeoDSS* spatial-modeling system to carry out dynamic surface and groundwater conjunctive use water quantity and quality modeling for river basins.
    2.1. Create a water quality module to perform conservative solute routing throughout the system and to provide the means to seamlessly interact with surface water and groundwater *River GeoDSS* components.
    2.2. Develop and implement a tool for in-line reservoir water quality transport through the reservoir for comprehensive river basin quality modeling.

2.3. Develop and implement an alternative methodology for efficient basin scale stream-aquifer quantity and quality interaction modeling, and predict the complex stream-aquifer processes for the river basin based on a detailed regional-scale groundwater finite difference flow and mass transport model.

3. Develop and implement tools to expedite and automate the calibration and simulation of the *River GeoDSS* modeling system.

4. Design and implement tools for comparison and analysis of alternative management strategies.

The *River GeoDSS* capabilities are designed to facilitate the decision making process of river basin managers, and are applied and tested in a real-world case study. The Civil and Environmental Engineering Department at Colorado State University (CSU) has been at the vanguard of data collection and modeling in the LARV since 1999 (Gates et al. 2006). Over these years, the CSU research group has compiled a comprehensive set of data and models for understanding the inseparability of water quantity and water quality system behavior. Earlier research in the Arkansas River Valley has allowed the building of an exceptional dataset collected over nine years at both regional and field scales. Salinity and waterlogging effects have been studied in detail. Management alternatives have been engineered and modeled at regional-scale to mitigate these problems and to support agricultural sustainability, environmental enhancement, and water conservation in the area (Burkhalter and Gates 2005; Burkhalter and Gates 2006). Irrigation activities with saline water require a comprehensive analysis beyond the area where water is applied. The basin-scale analysis of field and regional-scale developed solutions will reveal larger-scale benefits and impacts as well as the feasibility of their implementation within a highlyconstraint system. This case study is propitious for the *River GeoDSS* application since it can provide the tools necessary for analyzing at the basin scale the management strategies developed at the regional/field scales. Application of *River GeoDSS* to the LARV allows evaluation of large-scale implementation of alternatives to manage present problems and to develop efficient solutions to support a productive irrigated agriculture, to enhance the river environment, and to promote water conservation. The objectives of the *LAR GeoDSS* implementation are:

1. Assemble a robust geo-spatio-temporal database compiling the available digital information from CSU, the USGS, USDA, Natural Resource Conservation Service (NRCS) and others in collaboration with the Colorado Division of Water Resources (CDWR), water conservancy districts, canal companies, and other local agencies.
2. Represent the necessary system elements and the legal, administrative, and institutional rules to accurately reproduce historical weekly system operation while integrating hydrologic processes, water rights, storage accounts, water compacts, water exchanges, and physical system limitations.
3. Apply the *River GeoDSS* methodology to represent the stream-aquifer interaction at the basin scale using the available calibrated regional-scale groundwater model. The conjunctive use of water quantity and quality modeling will facilitate the screening of improvement strategies under appropriative water rights and other legal, institutional, and administrative structures in the basin for implementation decision making.
4. Evaluate river basin response to the regional-scale developed water management alternatives including improvements in irrigation practices, pumping patterns and infrastructure improvements such as canal lining and subsurface drainage installation.

5. Evaluate effects in water quality due to changes in reservoir operations, water use and management alternatives implementation.