

CONJUNCTIVE SURFACE WATER AND GROUNDWATER MANAGEMENT:
A NEW FRAMEWORK FOR STRATEGIC DECISION-MAKING

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CONJUNCTIVE SURFACE WATER AND GROUNDWATER MANAGEMENT:
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ABSTRACT

CONJUNCTIVE SURFACE WATER AND GROUNDWATER MANAGEMENT: A NEW FRAMEWORK FOR STRATEGIC DECISION-MAKING

by

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Conjunctive use of water, or the optimized use and storage of surface water and groundwater, has become increasingly recognized over the past decades as an approach that facilitates efficient management of water resources. Recent research on conjunctive management primarily relies on economic evaluations or numeric modeling for specific regions; however, less research has focused on variables such as water laws and government institutions that affect water management policy options. There is a lack of consensus on its appropriate implementation, and no single document provides key parameters and standards for successful policies and programs of conjunctive use.

Accordingly, the goal of this research was to identify and evaluate essential factors in conjunctive management. Objectives to accomplish this goal first involved evaluation of quantitative and qualitative components and their relationships in conjunctive management. Based on the evaluation results, a new decision framework for strategically understanding and designing a conjunctive program was created to support consideration and decisions concerning conjunctive management options. Finally, the research goal of determining key factors that support viable conjunctive management was demonstrated through application of the framework in the Rio Grande basin.

Previous research on conjunctive use management strategies provided an extensive body of literature regarding the efficacy of conjunctive studies and programs. Many programs recognized the predominance of balancing and optimizing surface water and groundwater supplies as well as the economic efficiencies possible through conjunctive use and the limitations imposed by the interactions between surface and subsurface water systems. In addition, some studies recognized the role of legal and social systems. Thus, this work initiated with research in understanding how these four systems – physical water, economics, water laws, and social – support conjunctive use concepts.

The research utilized previous conjunctive studies to better understand key elements. The studies were evaluated both within each study and across all reviewed programs, an analytical approach not previously applied. Models of water balance and economic studies, located around the world, were assessed for model goals, techniques, assumptions, and associated parameters and data ranges. Overall results demonstrated that conjunctive use programs are supported by common parameters that are applicable

regardless of site-specific factors, geographic location, or model design. The results also illustrate the flexibility inherent in conjunctive use concepts.

Factors qualitative or subjective in nature were also evaluated for their relative effects on viable conjunctive management. To address possible issues of legal support for conjunctive programs, water doctrines and laws in five western U.S. states were assessed for their potential impacts on conjunctive programs. The assessment indicated that, despite varying development in each state's water law framework and differences in statutory and case law, conjunctive use programs progressed over time in each state and furthermore, created unique program activities in response to legal concerns. In addition, societal and stakeholder perspectives on conjunctive use programs were studied using a survey of and interviews with water management researchers and professionals. Analysis of the survey and interview results suggested gaps in agreement, even within the water industry, of what conjunctive use is and how the approach can be implemented.

Based on the research results concerning quantitative and qualitative factors, a conjunctive strategy decision framework was created to support improvements in understanding, designing, and implementing conjunctive strategies. A new conceptual model, minimum criteria, and a decision matrix of conjunctive components and external factors comprised the framework. The conceptual model incorporated seven major components of regional, surface water, and groundwater systems, ecosystems, economic/financial issues, legal/institutional frameworks, and social/stakeholder input. These components established the foundation of the framework.

Key criteria necessary to design a conjunctive strategy were developed from analysis of the major components. The criteria were compiled for each component and

used as a basis for evaluation of conjunctive goals. The matrix detailed the relationships between major components and external factors, including parameters identified through evaluation of previous conjunctive models, studies, and programs.

The conjunctive decision framework was prepared to support decisions concerning conjunctive strategies. Development of the framework was formed with the knowledge that water user groups and water professionals do not necessarily share an understanding of conjunctive use and its benefits and limitations. To test its efficacy, the framework's criteria base was applied to the Rio Grande basin of the southwestern United States. The basin was selected based on its unique geographical, social, and ecological features and the water-stressed conditions varying from floods to droughts that the basin has periodically experienced. Within the basin, the region selected for application of the framework was the lower Rio Grande valley. Existing technical reports and water management planning documents were utilized. The majority of criteria were addressed and integrated with existing information, thus theoretically minimizing program design costs. However, review of the reports and documents showed that planning teams in the region have yet to fully realize conjunctive goals, strategies, standards, and an efficient approach to achieve an operational and successful conjunctive program. The framework can provide a path for achieving the overall goal of improved water management in the region.

Currently, conjunctive management is undergoing a revival of interest in how a conjunctive strategy can aid or improve future water management. Previous programs, particularly those initiated several decades ago, focused on large-scale projects. This research, including review of multiple models, programs, and the closeness of fit between

targets and achieved efficiencies, indicates that local- to regional-scale programs, rather than state-wide programs, may be likely. The conjunctive strategy framework aids in evaluation of conjunctive management goals and a wide range of site conditions. For example, at the local or municipal scale, an aquifer storage and recovery program may provide a cost- and time-effective approach to managing low water flow or drought conditions. To streamline costs, conjunctive strategies that incorporate groundwater storage capabilities appear to best support rather than replace existing water management programs. In addition, conjunctive optimization can occur through multiple technical approaches that fit site-specific needs. The information, data, and decision framework presented in this research address gaps in understanding and implementing viable, long-term conjunctive programs.

CHAPTER 1

INTRODUCTION TO CONJUNCTIVE WATER MANAGEMENT

Introduction

Many watersheds of the southwestern United States exhibit known, demonstrable, and complex water issues, including water shortages, flooding, non-flows along several river segments, and water quality challenges. This research focuses on the possibilities inherent in a long-term approach to water management with the flexibility to address and aid in mitigating such issues, an approach known as conjunctive use or conjunctive management. Simply stated, it is optimal use of water sources over time when more than one water source is available at the same time. In theory, it is straightforward to use one water source while another source is being conserved, stored, or replenishes subsurface sources. In reality, the conjunctive approach has been perceived in some regions as difficult to implement in practice, particularly when other water management tools have been utilized for years. However, in the last few decades, water-stressed regions have experienced difficulties in providing water to growing populations with concurrent increases in water demands. The difficulties inherent in balancing past water projections with current supplies, demands, and unforeseen factors such as changes in climatic conditions suggest that the time is right to reconsider the fundamental strengths in

conjunctive water management. Over the decades since recognition of conjunctive use as a water management strategy, it has been recommended in research and policy documents. Definitive methods for implementation, however, are rarely included in such documents, indicating a lack of knowledge and/or agreement on which scientific, economic, and political factors determine whether conjunctive management is a viable water management strategy for a specific region. Although conjunctive management is recognized as a water resource approach, it can be complex to plan, develop, organize, and execute conjunctive strategies without a broad-based understanding of conjunctive management. Water managers and providers lack a consensus on the appropriate implementation of conjunctive use. Furthermore, no single document provides key parameters and standards for successful policies and programs. This research addresses such gaps through a methodical evaluation of the primary factors supporting conjunctive management of water supplies.

Conjunctive Use: “It Depends ...”

Quantitative research on conjunctive management has previously relied on economic evaluations or numeric modeling for specific regions; however, less research has focused on variables and constraints such as water laws and government institutions that affect water management policy options. Discussions with water management professionals about a definitive understanding of the term “conjunctive use” typically begin with the phrase, “It depends.” Indeed, viable conjunctive use programs must cope with primary input of water sources, limits on water uses, costs of planning, infrastructure, and operations, seasonal variations in water availability, required outputs, and other primary factors, making conjunctive use no different than other management

strategies in this aspect of dependency upon variable water sources. Water management approaches must also have an understanding in place of the framework within which operations will occur. Societal and environmental concerns may be critical to the success of a water management program as are its water balance model and targeted thresholds of supply and demand.

Adding to the idea that conjunctive use is rather vague, almost every publication provides a definition aligned with the discussed study's goal and focus. While a flexible approach to understanding conjunctive use is important in getting projects to the planning stage, variations in understanding, technical approaches, and goals can add to general confusion about its applicability. For this study, the definition of conjunctive use is: *the optimized use of surface water and groundwater supplies, such that one source allays the temporal or spatial shortcomings of another source through additional supply or storage options, and that interconnections of water movement between the sources are part of the optimization and assessment of potential impacts.*

Development of Conjunctive Use

Conjunctive use of more than one water source likely has been utilized ever since humans developed the ability to transport water and dig wells. More formally, conjunctive use as a water strategy was discussed in a study discussing the economic advantages inherent in groundwater storage (Banks 1953). Interest and research in the strategy subsequently increased. Economic factors, positive and negative, were assessed in hydrology texts (Todd 1959). Linear optimization techniques were applied in an allocation model for agricultural areas (Castle and Lindeborg 1961), while programming of algorithms and large data sets were used to explore design and operations for dams and

aquifers in agricultural applications (Buras 1963). Groundwater valuations based on stochastic modeling of an “optimal inventory policy for ground water” firmly identified conjunctive use as a viable water strategy (Burt 1964). Studies of conjunctive use continued to focus on economic analysis and agricultural efficiency for several more decades (Gisser and Sanchez 1980; Feinerman 1988; Tsur and Graham-Tomasi 1991; Knapp and Olson 1995). Young and Bredehoeft (1972) were the first to address the problem of simulating groundwater withdrawal effects on river flows and the associated economic responses by water users to changes in water-flow volumes and costs. Conjunctive use was analyzed in terms of systems and levels of associated issues (Maknoon and Burges 1978) and optimization of operations and controls for agricultural and urban water uses (Noel et al. 1980). With the advent of improved computing power, conjunctive use research began to incorporate large data sets in numerical models for basin-scale water availability and resource management decisions. Selected examples of such models are found in the reports of Papadopoulos and Associates (2000), Barlow et al. (2003), Cai et al. (2003), Fleckenstein et al. (2004), Rao et al. (2004), and Booker et al. (2005).

As a water management strategy, conjunctive management has been recommended by policy analysts and decision makers. Under Texas Water Development Board rules, for example, a required goal of a groundwater conservation district’s management plan (31 Texas Administrative Code, 31 TAC 356.5) – need TWC is to address conjunctive management of surface and groundwater. However, the code does not include specifics on implementation of conjunctive management. In 2004, a Texas Senate Committee was tasked with reviewing water policy issues for the state. Although

one recommendation included “Conjunctive Use of Both Surface and Ground Water Sources” (Texas Senate Select Committee 2004), none of the report’s attachments explicitly discussed the practical execution of conjunctive management.

Current conjunctive management programs have different goals and therefore varying designs and operation requirements. The California Department of Water Resources, for example, focuses on local partnerships and needs for those local basins (CDWR 2010). The Central Arizona Project deals with large groundwater overdrafts through a large canal that transports water from Lake Havasu on the Colorado River, thereby serving municipal, industrial, agricultural, and tribal nation users (CAP 2009). Internationally, organizations such as the Consultative Group on International Agricultural Research (CGIAR) of the International Water Management Institute (IWMI) may include conjunctive management in specific projects (IWMI 2009). Each project has its own approach, thereby providing site-specific information and insights as to appropriate implementation of conjunctive use.

Purpose and Objectives

This dissertation study identifies and queries the primary factors underlying each major aspect supporting viable conjunctive management. Major aspects – legal framework, economic efficiency, physical characteristics specific to watershed and aquifer, and social water use issues – are aspects shared by other water management strategies. Unlike other strategies, conjunctive use within developed areas may require little in the way of additional facilities. Rather, conjunctive use encourages use of water through alternately using surface water and groundwater within the context of their most optimal capacities. To best determine the optimal use per water source, regardless of

location, this research addresses the question of what are significant parameters and factors of conjunctive use. To address these questions and associated issues, the following objectives are an integral part of the research:

- 1) An evaluation was made of quantitative and qualitative components in conjunctive management, the relationships between components and external factors, and the end results of conjunctively managing alternative water sources.
- 2) Analysis of relevant parameters and relationships within a logical methodology take into account major program considerations to date, and are presented in a new framework – a conceptual model, criteria, and matrix of conjunctive components and external factors. The framework is prepared to support policy decision-making towards consideration of conjunctive management options. With detailed modeling techniques, water conservation measures and support for ecologic flows and habitats can be included in the water management targets.
- 3) The primary goal of determining key parameters and qualitative factors that allow viable conjunctive management is demonstrated through application of the decision framework to a water-stressed region, the Rio Grande basin.

Brief Description of Methods

The research relies on published models and studies to assess factors that allow successful model projections. The majority of previous publications focus on one or more aspects of economic, water balance modeling, and legal/institutional frameworks in conjunctive use. Results of an online survey conducted in this study, it became apparent that the social component has a critical role to play in the selection of future water

management options. Each of four primary aspects of conjunctive use programs, therefore, is evaluated in this body of work.

The physical systems of surface water and groundwater are the physical basis of conjunctive use programs. Without appropriate physical characteristics, conjunctive use is not appropriate as a strategy for water management. Therefore, suitable characteristics for surface water and groundwater systems are defined through current research sources, evaluation of conjunctive use models and programs, electronic survey, and interviews.

Economic considerations are a key part in developing and implementing water management strategies and alternatives. If a management option is not economically viable for the system and society, then generally that option is not taken past the planning stages. Economic algorithms, proofs, and models have been one of several analytical approaches to address research questions or program systems and considerations. The proofs and models are quite specific to the study or program. However, the building blocks of the analysis, or parameters selected to utilize in the modeling tools, are informative as to the basics of conjunctive use. A review and in-depth analysis of economically based models is conducted to determine common and unique parameters of conjunctive use.

Legal systems that allow or disallow conjunctive use in five western states are reviewed for their impacts on conjunctive use programs. These different legal systems allow comparisons of the development of conjunctive use where the approach is frequently used and for states where it is less known. The contrast in legal systems also allows discernment of how conjunctive use might be adopted in regions where it is not currently considered a significant option for future water management.

Societal impacts on water management decisions in today's world cannot be underestimated. Whereas in previous decades of water management decisions generally tended to be created at the state and federal level, the current situation of water concerns at the individual user's level, notwithstanding the encompassing needs and issues at a river basin or aquifer level, has resulted in a large amount of societal input to many aspects of water management decisions. Based on identification of these needs, a societal/stakeholder component is explored in the research through survey and interviews.

The results provide the basis of a framework to serve as a basis for the knowledge base and decisions about conjunctive management, prepared for a water management planning team, including decision-makers and stakeholders concerned with conjunctive use as an option for future water management. The framework is prepared in three parts. A conceptual model allows visualization of basic components and other factors in conjunctive programs; criteria fundamental to conjunctive management are developed for each component of a conjunctive program; and a matrix of components and external factors is prepared to guide a water planning team through shared concerns in evaluating conjunctive use as a possible option for future water management in their region.

To test and demonstrate the relevance of the conjunctive decision framework, the approach is applied to the Rio Grande watershed, a region that encompasses diverse landforms, habitats, physical water systems, and urban, rural, and highly agricultural communities. Conclusions and recommendations for future considerations of conjunctive management are included in the final chapter.

Overview of Dissertation Chapters

The dissertation is composed of this introductory chapter followed by four chapters focusing on the primary components of conjunctive use that underlie its success as a water management approach, two chapters that propose and apply a conjunctive strategy framework founded in the preceding analysis of the four components, and a final chapter of conclusions and considerations for the future of conjunctive use as a water management approach. Four chapters have been prepared for submission to appropriate journals. While the dissertation text is formatted in the style required by the Graduate College, Texas State University-San Marcos, references of chapters intended for submission to journals are prepared in the style of the specific journal. Otherwise, references are prepared in accordance with the style required by the Council of Science Editors, formerly the Council of Biological Editors.

Chapter 2 targets physical water systems of conjunctive use, e.g., surface water sources and aquifers in areas of water management interest. Physical systems and their parameters are assessed through evaluation of water balance and integrative discipline models. Results suggest that while appropriate physical systems must be the first basis to determining whether a conjunctive management approach is appropriate to a specific water issue, under which conditions conjunctive use may be applied can vary widely.

One of the economic foundations of conjunctive use, parameters used in building economic-based models to evaluate conjunctive strategies, is the focus of Chapter 3. A review of economic models involved in conjunctive use is conducted, followed by comparison and evaluation of parameters common to the models, as well as those unique to a particular study. The analysis provides insights into the parameters that may be

considered in a decision document of conjunctive use. This chapter is written in the Ecological Economics journal style.

Chapter 4 is concerned with conjunctive use and its basis in selected state legal systems in the southwestern United States. Analysis of laws and the associated development of conjunctive use programs are discussed for five states with different legal frameworks for handling water management. The conjunctive programs in these states vary widely, from viable, long-term programs to administrative rule conflicts that reflect the differences in state water laws. The comparative results are used in determining possible foundations for future consideration of conjunctive use. The chapter is intended for submission to the Natural Resources Journal with legal style citations.

Another component of successful conjunctive programs is societal and stakeholder interests, particularly as related to future water management options and decision-making. To understand how these qualitative and subjective aspects interact in the overall concept and actual implementation of conjunctive use, the results of a survey and interviews with water management professionals is discussed in Chapter 5.

Results of these evaluations, in addition to identification of gaps in the body of work concerning conjunctive use, provide the basis for creation of a conjunctive strategy framework. Composed of a conceptual model, criteria, and matrix, the framework is proposed for use by water management planning teams, decision-makers and stakeholders. The end goal of its utilization is for such groups to become better informed about the strengths and benefits possible through application of conjunctive strategies. Chapter 6 discusses the framework and underlying concepts and basis. The chapter will be submitted to the Natural Resources Forum.

Chapter 7 reviews physical water and legal systems of the Rio Grande watershed, its socio-economic conditions of major urban water demand centers, as an overview towards the applicability of conjunctive management. Selected projects indicate the applicability and potential of conjunctive management in the basin. The conjunctive strategy framework is applied to the lower river valley in the watershed to highlight the strategy's relevance. Chapter 7 is prepared for submission to the online journal, *Water Alternatives*.

Lastly, the cumulative results of the preceding chapters are discussed within the context of the future of conjunctive management as an approach and a strategy rather than a water supply program that is isolated from other concerns in a region. Conclusions from the different topics are reviewed, and their implications for policy decisions of water resource management are discussed. A cost comparison between water management approaches highlights the disparities and possible economic impacts of selecting certain water management approaches. The results suggest that conjunctive management is currently undervalued in some water-stressed regions that would otherwise benefit from implementation of the strategy. Real-time concerns for finite water sources, increasing population centers, and concurrent increases in water demands, require that current water management tools be re-evaluated in regard to their viability and effectiveness in light of changing demographics, climatic conditions, and societal views on water supply and demand.

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CHAPTER 2

CONJUNCTIVE WATER SYSTEMS, MODELS, AND PARAMETERS

Conjunctive water projects begin with one major assumption, that water systems of a study or a management program are available and appropriate. One reason may be the implicit assumption that the process of selecting a water system, surface or subsurface, is obvious due to its presence or its unique features. However, few studies or programs assess water management in terms of which essential physical factors allow conjunctive water management to be viable, regardless of location, duration, or phase of operations.

This chapter focuses on the knowledge gap concerning physical water factors that support conjunctive management. Specifically, the physical water systems themselves are a major component of conjunctive water management and, in some ways, the foundation, of successful conjunctive use as analyzed in this research. To this end, this chapter addresses key conjunctive aspects of physical water systems, including explicit and implicit parameters, constraints to their use, and the evaluation of water balance and decision models associated with conjunctive water management. The purpose is to identify and clarify the basic parameters necessary for planning and implementing future conjunctive use programs, as well as parameters unique to certain models and studies. The results are discussed from the perspective of water managers and planners may wish to examine for future water management options.

Due to the predomination of the term “conjunctive use” in the reviewed body of literature, as well as “conjunctive management” to a lesser degree, the terminology in this chapter will mirror its use in various publications. Therefore, the two phrases may be somewhat interchangeable in the discussions. Where possible, “conjunctive use” will reference previous studies or the original concept of optimizing surface water and groundwater sources, while “conjunctive management” will be applied to conditions and studies that involve water planning and management strategies.

Background and Context

Conjunctive Water Systems

Since the concept of conjunctive use was first proposed and expounded (Banks 1954; Buras 1963; Burt 1964), research studies and projects tied water usage with economic theory, agriculture practices, and water control. Few, if any, studies focused solely on water system factors of conjunctive use. To address this gap, this chapter concentrates on the essential factors of physical water systems.

Water is a study of hydrologic concepts, systems, components, and natural factors, being in various ways the subject of countless previous publications. Textbooks examined throughout the course of this research concerning surface water included Dunne and Leopold (1978) and Dingman (2002). Those that focus on groundwater included Freeze and Cherry (1979), Fetter (1994), and Todd and Mays (2005). Although it is not possible within the scope of this research to encompass the disciplines and sub-topics comprising such knowledge, a brief summary of water systems is given herein as context for the subsequent research methods and results discussed in this chapter.

An evaluation of water systems that support or allow conjunctive management appears to be simple and straightforward. One such view is a system of pipes, or water flow along natural streams and human-made diversions, and buckets, or natural or man-made reservoirs. Available surface water is diverted for use through diversion points, canal systems, and pipes. Groundwater is often a secondary source and is accessed through wells to allow pumping of groundwater that can, in turn, be piped to water demand areas.

An illustration of this over-simplified approach to a conjunctive water system is presented in Figure 2.1. The diagram is comprised of three factors: (i) surface water in a “pipe” or stream; (ii) surface and subsurface water stored in “buckets”, or reservoirs and aquifers; and (iii) flow movement along vectors portrayed as arrows in the diagram. The visual simplification sums up one view of conjunctive use, that of an engineered system. For anyone who appreciates the beauty of a river and the complexity of a watershed, an engineered system cannot define its whole. Such a simplification aids in understanding the basic concepts of conjunctive use but does not define conjunctive strategies or physical water systems.

Water systems may also be perceived as a supply-and-demand resource to humans. Water is needed, made available through an array of storage and canals, and put to use. Water uses are assessed and calculated to be more or less efficient. Yet water also moves through a much larger dimension – that of surrounding landforms, geology, climate, and modifications through land use. To be viable for the long term, water management strategies must consider factors beyond water uses and efficient supply and demand.

What might be considered appropriate sources of surface water or groundwater for conjunctive management? Beginning with surface water, a well-defined, channeled river or stream system is a likely base. A natural lake is a possibility but is not as versatile in providing water for hundreds of miles which a stream system can do. The stream should have sufficient flow with rates measured in seconds to minutes, fairly-well defined peaks and lows, and should discharge to a larger system. Furthermore, one or more reservoirs often have been created along major river stretches to provide water storage and to smooth out fluctuations in streamflows over time. Rainfall or snowmelt in the basin provides sufficient seasonal input to keep the system recharged. Soils and bedrock within the watershed would ideally have characteristics of sedimentation rather than high erodability. Natural water quality would be high, requiring little treatment prior to use.

Groundwater systems ideal for conjunctive use have different characteristics of interest. As with surface water sources, water flow, storage, recharge, discharge, and water quality are basic parameters of the system. The time and geospatial scales of groundwater systems, however, are much different than those of stream systems. Water flow and storage occur within distinct hydrogeologic strata, and in turn are affected by that media, particularly as the strata may have differing characteristics within one aquifer. A stream moves through the landscape in a linear pattern, branched at the joining of other streams. In contrast, an aquifer can occur in many forms. Groundwater may be found, for example, in small, lenticular sedimentary layers, multi-layer strata, extensive limestone formations, or alluvial valleys. Whereas stream flow and its recharge is measured in seconds or minutes, groundwater flow is more often measured in hours to

days within fast-moving systems such as karstic limestone, or in months to years for groundwater recharge percolating through sandy aquifer strata. Groundwater discharge can take different paths, such as pressurized discharge to springs, shallow movement as stream base flow, or flow into another set of geologic strata. Depending on the soils and underlying geologic strata, the quality of groundwater can be very good and require little treatment prior to use.

The above descriptions give a brief overview of basic surface water and groundwater characteristics but do not begin to identify parameters of interest to conjunctive use that is the purpose of this chapter. Instead, the research utilizes peer-reviewed information, papers, and programs which provide extensive information within the desired context – conjunctive use and management – and allow an in-depth assessment of physical water system parameters.

Other factors and interactions in the natural water system are as important as water sources with conjunctive use characteristics. One major factor is interconnectivity between surface water and shallow groundwater. Given time, little human interference, and appropriate geographical and geological conditions, water typically moves across the landscape as well as infiltrating and percolating into the subsurface. Dependent on the seasonal aboveground and subsurface water levels and conditions, groundwater may provide water to streamflows, or water may percolate down to the groundwater level. If a water management strategy does not take this hydrological reality into account, the system may store and yield less water than expected, particularly under stress or changes induced outside the anticipated operation of the system. The two systems display flows differently in time and space, characteristics which can be difficult but not impossible to

capture in a water balance model. Furthermore, flows and storage volume in either surface water or groundwater can be affected by changes in the other as connected by flow interactions. In a connected regional water system surface water flows may be decreased by groundwater extraction that takes place at a greater rate than does replenishment of the stream through inflows and rainfall runoff. Conversely, groundwater storage may be lessened in physical systems where streams are the primary recharge mechanism and where those flows decrease to the point that groundwater storage measurably decreases. Conjunctive management can include quantifiable interactions in water balance and availability modeling, but the underlying assumptions must be carefully reviewed for the effects that such modeling assumptions and their associated algorithms may place on understanding real-time water movement and storage.

Conjunctive Modeling and Optimization

As noted in the previous simplified discussion of basic physical factors important to conjunctive use, the creation, testing, and application of models is a discipline that extends beyond the scope of this study. An overview, however, provides a context of why water balance models were selected for evaluation in this research. Water balance models have been used for decades and play a significant role in planning and operating various water management strategies. A model appropriate to the water management goal or goals is key to a study's successful outcome, as are its inputs and assumptions. If a model can approximate the water system under consideration, then projections of changes in the system from stress variables inputted to the model allows for projections of various future outcomes.

A water system model requires a concept of its physical setting and the problem being addressed. The concept is typically expressed in diagrams at a base level and then separated into mathematical expressions. Software or other written code and algorithms, specific parameters, and assumptions aid in translating the concept into a working model.

Every model needs a framework and context within which to operate, and the models examined in this chapter focus on water management. To understand modeling of conjunctive management planning or operations, previous modeling endeavors can provide data and information. Considering the number of conjunctive use models in the literature, creating another model does not necessarily lead to greater understanding of conjunctive systems. Nevertheless, a review of existing models can provide insights, if the right context is considered. The appropriate context in this case is the concept of conjunctive use.

Reviewed water models were termed physical system models, water balance, numeric, or multi-objective algorithms for decision-making. The phrase “water system models” will be used to discuss the subtleties of creating a model that reflects a specific portion of a watershed and its associated aquifer(s).

Conjunctive management also utilizes optimal scenarios to formulate and realize model goals. Optimization approaches may include issues of sufficient water supply distribution, storage, and/or economic targets. Conjunctive use as a concept for managing water resources requires an understanding of the physical water systems and how they might be simulated in order to project future changes in the system when relevant variables are modified. Simply stated, to optimize is to “...to make as perfect, effective, or functional as possible” (Webster 1983). For conjunctive use, optimization

can be simplified to comparison of desired targets (e.g., a minimum river stage during low flow months) to outcomes of different model simulations. The key to optimization is not necessarily the algorithms used to calculate possible outcomes, but rather it is the target. A water management team must examine whether the management target is clear, measurable, repeatable, and relevant to anticipated water issues that may result from application of the optimized and refined model to the actual program. The efforts in this chapter include the optimization criteria used by different models and programs. Although each optimization approach was found to be unique, the associated results were a significant part of successful conjunctive programs.

Research Methods

To better determine how physical systems interact with a conjunctive approach, numeric models that focus on water balance budgets were analyzed in the context of conjunctive use fundamentals. The evaluation included analysis of information pertaining to conjunctive use aspects as well as basic similarities and differences in parameters and data. The data sets were comprised of information, data, and results compiled from reports of selected models. The evaluation specifically covered general information and a summary description of each model, including the model goal, an overview of the model's hydrologic approach and software, optimization criteria, and major results. Comparison of the modeling approach per project also was included in the analysis; namely, which models are similar and why? This approach allowed an in-depth analysis of each model, and the resulting summation of model goals, factors, and results facilitated an analysis not only within each study but also across the studies. Results of

this analysis were then utilized to support the creation and synthesis of a framework for conjunctive management decision-making (Chapter 6).

Models were selected on the basis of two main criteria. First, the project or model emphasis must be on evaluating water resources as a system for answering a larger question about the resources and, second, the project or model must explicitly recognize conjunctive applications of surface water and groundwater. Fifteen models were selected for assessment of conjunctive use parameters and other relevant factors.

Examination of the framework of each model allowed identification of parameters common and unique to a conjunctive approach. Because each modeling approach was developed within the context of project goals, specifications, and requirements, each model also provided a set of independent data and information. Parameters and data specified by the models regarding background information, surface water data, and groundwater data were compiled to evaluate parameters associated with a conjunctive approach (see Appendix A). From this compilation, parameters were selected for the criteria of commonality or uniqueness among different studies and programs, and the support of conjunctive, optimized water use.

Under these conditions, the published models were assessed for:

- Overall project goal or goals (i.e., the problem to be addressed through the modeling effort), and
- The approach to numeric water modeling, or other means of quantitatively assessing the water data, optimization criteria, major results, parameters commonly used in the models and others unique to a study, and other factors and considerations.

Finally, the reported data were analyzed as a group per common category, allowing low and high values. These parameters and data were then used to develop a more exact framework of the conditions under which conjunctive use of water sources might best be considered for water management.

Results and Discussion

As discussed below, the results of compiling and evaluating information and data from conjunctive water system models are grouped into three sections: (i) general model contextual information; (ii) water system parameters and factors; and (iii) identified data ranges. Additional materials are provided in Appendix A.

General Model Information

To understand the context in which each reviewed model was created, Table 2.1 summarizes general information. The reviewed publications and associated models often contained extensive detail; therefore, selection of pertinent categories of information revolved around several questions. Did the information focus on the context within which conjunctive management played a role in the research study? Did the category provide sufficient synopsis of detail so as to inform the reader about different aspects of conjunctive management? The ultimate categories were selected after review of the models, separately and as a body of work, indicating strengths and constraints of conjunctive use applied to specific regions and problems.

The reviewed papers were published during the period from 1983 through 2004. As noted in the Background section of this dissertation, published work on this topic extends to the 1950's and models from the early 1960's. The reviewed publications were based on research locations in the United States varying from the east coast of the United

States (Rhode Island), to the central plains of Kansas, to the west coast of California. International locations of research interest included the Syr Darya river basin of the Aral Sea, River Shiyang in northeastern China, the east coast of India, and West Sumatra, Indonesia. The project locations and geographies varied, but all involved common management issues of surface water and groundwater, particularly under conditions of hydraulic connectivity between surface water and groundwater. All of the study areas had existing infrastructure and human water demand centers.

Project goals varied widely. The water system models addressed questions of water use alternatives, pumping effects on surface water levels, tradeoffs or options for different management decisions, the effects of drought, water quality degradation, decreases in storage, changing economic conditions, and assessed an environmental water management issue of potential stream flow targets to support annual salmon runs. Considering the different project goals, this variability demonstrates yet again a fundamental strength of conjunctive management; namely, its applicability to different geographic and water management decision conditions. For the purposes of this evaluation, the model results (summarized in the right-most column of Table 2.1) are less a factor of conjunctive use than a determination of how closely the model goal was achieved.

Model descriptions provided a different insight, that of variation between models. As might be anticipated, no two models were alike. As much as geographic, geologic, and issues-based characteristics were factored into each project, the perception of which physical water source dominated the water management problems also informed the choice of a model and its basic assumptions. Thus, the model description category in

Table 2.1 included the predominant software base and model components. The software base or “centric code” characterization in Table 2.1 facilitated understanding of the conjunctive models, highlighting the diverse requirements for addressing water management. Inclusion of the basic software helps to explain limitations of each model.

Surface water-centric software focused on detailed parameters of surface water, typically river flow. In addition to river inflows, model parameters might, though not necessarily, include timed reservoir water releases, irrigation return flows, and groundwater base flow. One surface water-centric software was the HEC-PRM, developed by the U.S. Army Corps of Engineers. Utilized groundwater-centric software was typically a version of MODFLOW, wherein groundwater flows in and out of grid cells to approximate hydraulic head changes over time (McDonald and Harbaugh 1988). Of the 15 reviewed models, five were based on surface water-centric code; four on groundwater-centric code; four on integrated results from sub-models; and two were multi-objective, weighted function algorithms. Distinguishing these fundamental modeling differences allowed recognition of the modeling predisposition towards fundamental issues of water management issues, perceived best approaches for modeling conjunctive use, and better understanding of the model’s limitations and constraints on its projections.

An example of assumptions noted in the software characterization was observed in the “surface water-centric” label. These models tended to lump groundwater parameters into a single tank model, an example being the simple single-tank model of Bear (1977). The Bear algorithms approximated groundwater functions at a very basic level with inflows, outflows, and change in storage, but did not allow more detailed input

of parameters, thereby resulting in model runs that at best only approximated groundwater-driven scenarios. Whether a lumped parameter approach was appropriate to a model was typically best determined by the modeling and water management team. The significant point in each study was that the team agreed upon and explained the limitations of input, computer simulations, output, and scenarios of future water management to decision-makers and stakeholders. To use the same example, if a model uses the lumped parameter approach for a complex aquifer system, simulation results may not match realistic storage and groundwater movement in support of any water management program.

Table 2.1 also summarizes optimization criteria, which varied as widely as the simulation modeling approaches. Optimization criteria, or targets, included surface water minimum flows in conjunctive with groundwater pumping regimes, maximum groundwater pumping levels that do not deplete stream flows, water right priorities and their effects on stream flows, economic tradeoffs, and operational parameters of existing water management systems. As with the models, variability in creating and applying optimization rules reflected the flexibility inherent in a conjunctive management system. While optimization rules may be created for a wide variety of programs and water management goals, it is critical to understand the applications, assumptions, and limitations of each set of optimization criteria.

Water System Parameters and Other Considerations

Can parameters, common and unique, aid in determining the limits of conjunctive management? This question was explored through evaluation and comparison of parameters in selected conjunctive water system models. Each physical system model

was reviewed and assessed for its water system parameters and the data compiled. Because some of the models indicated that complete data sets were not presented, or referenced the software manuals, the list of parameters was considered indicative of conjunctive use domains rather than being a complete list of all parameters that might possibly be required by any conjunctive use model. The results are shown in Table 2.2.

Explicitly noted terms included major inflows (upstream flows, reservoir discharges, irrigation return flows, groundwater lateral inflow), outflows (water use, diversions, evaporation, downstream flows, aquifer outflows, pumping), and terms that numerically express connectivity or “leakage” between surface water and groundwater. All these quantitative parameters, and more as required to complete inputs for specific models, can be expressed as numeric constants or variables. The listed common parameters should not be considered a complete list but rather a starting point for decision-makers and stakeholders interested in the viability and applicability of conjunctive water management.

Equally important is the list of “Other Factors” noted in Table 2.2. Every model contained one or more unique features. Land and water uses varied due to geographic locations and human populations. Benefits and costs were often considered, even when not explicitly written into the model code. Furthermore, the legal/institutional impacts played an important role when present in a given study area. Some factors such as costs were expressed quantitatively, while others were qualitative, thereby being more difficult to include in a model.

Striking results of the parameter evaluation and compilation are:

- A difference was observed in the date of model preparation. Algorithm, two-dimensional models of the 1970's and 1980's tended to have small numbers of parameters versus large sets of parameters and data associated with water balance modeling and greater computing power in the 1990's.
- Among the diverse projects discussed in the literature, the common parameters focused on water movement and storage. Parameters associated with other issues such as water quality, environmental concerns, and impacts of institutional controls were site-specific but did not necessarily target the conjunctive use concept.
- The breath of conditions that were considered under a conjunctive management program is noted in "Other Factors." A successful conjunctive program would do well to evaluate these factors in addition to model-driven parameters.

The common water system parameters and other unique factors provide appropriate input to the formulation of a framework for conjunctive management decision-making, the subject of Chapter 6.

Boundaries and Constraints

Due to the flexibility of the conjunctive approach and its potential for application to wide-ranging locations and water management issues, there are inherent difficulties in determining limits on conjunctive management. Another way to state this problem is to ask the question: When should conjunctive management be applied, and when should it not be considered? To address this challenge, the selected model population under review was also evaluated for specified data ranges. The goal was to consider the

conjunctive approach within characteristics that would support placement of boundaries on conjunctive water decision-making.

The results of the data evaluation are shown in Table 2.3 with all data converted to the metric system. Tables in Appendix A summarize the compiled information and data as reported in their original units of measure. Table 2.3 contains three sections – general background data, surface water systems, and groundwater systems. An overview of the data ranges is as follows.

The smallest study area was 49 square kilometers (km^2), while the largest was 8,784 km^2 within a regional basin of 30,000 km^2 . Precipitation varied greatly, ranging between 10 and 290 centimeters per year (cm/yr), suggesting that regions other than semi-arid to arid basins may consider conjunctive use a viable water management option. Many of the reports indicated that seasonal variation was part of the studies water issues. Water uses also varied greatly, although the predominant uses were those involving the greatest water volumes, agriculture and municipal/urban. The frequency of reservoirs in the models suggests that flood control, recreation, and aesthetics may also be part of the system but not necessarily considered part of the model. In contrast, environmental flows and hydropower were infrequently reported in the researched studies.

Commonly reported surface water data were the annual average flow rate into the system, ranging from a low of 0 cubic meters per second (m^3/s) to a peak of 2,650 m^3/s , this range being reported for the same water system. Data on infiltration of surface water into the vadose zone were more consistent than flow rates – the low and high infiltration rates were slightly comparable at 0.59 to 0.74 m^3/s . It was anticipated that parameters such as channel width, roughness coefficient, and river segment lengths would be

discussed; however, with the exception of precipitation, little data were reported at the watershed scale. Depending on the software or code, model input may require more parameters to allow appropriate simulations.

Of significance to conjunctive use is the frequency of reported stream-aquifer connectivity (12 of 15 models). The other three studies may have had some degree of interconnectivity but, due to the very large scale of these models, all possible parameters were not reported. The presence of interconnections between a surface water body and subsurface groundwater systems suggests that a conjunctive approach grew from problems resulting from one over-extracted water system that reflects depletion or other related problems in the linked water system.

Parameters for groundwater systems tended to have more information and discussion reported than surface water-centered models. While the majority of models dealt with one groundwater basin, one regional-scale, inter-tied model reported more than 28 basins in the groundwater portion of the model. Principal groundwater flow characteristics (system recharge, hydraulic conductivity or transmissivity, storage, and pumping rates) exhibited great variations, which might be expected of the primarily-alluvial aquifer systems. The range of reported hydraulic conductivities (61 to 243 m/d), was also indicative of porous, permeable formations, but not sufficiently permeable or fractured such that groundwater storage was unlikely.

The ranges of total annual pumping in the modeled systems reflected their moderately conductive and productive characteristics over time. For large water systems with more than 1,000 wells, pumped groundwater volumes were correspondingly high (Yang et al. 2001). In systems with a moderate number of wells (30 to 100), the annual

volumes of pumped water were lower (Barker et al. 1983; Fleckenstein et al. 2003). For the system with the lowest number of wells – 18 – the annual volumetric rate of water withdrawal was much lower. However, in each of these four studies, a strong water management concern was the sufficiency of future groundwater in the system. No matter the size and productivity of a system, it was recognized that an aquifer can be over-exploited.

To summarize the results of the water system data evaluation:

- The study areas and basins indicated that conjunctive water management as a strategy and as a specific program were not necessarily limited by area.
- The average annual precipitation variations (10 to 290 cm) in the model regions indicated that tropic as well as arid regions may be suitable for conjunctive water management.
- Compared to other potential water uses, agriculture and municipal/urban water volumes predominated in the model consumption calculations.
- Stream flow rates into the system varied, suggesting that there is no one baseline. Consideration of a stream's variability over time and the possible outcomes of the variability were more important than a base rate in conjunctive management.
- With the exception of precipitation, little data were reported at the watershed scale.
- Twelve of 15 models reported stream-aquifer connectivity. It is possible that study areas were selected for this characteristic; however, it is likely that such regions of interconnectivity dominate conjunctive management program locations due to the presence of surface water and relatively shallow groundwater.

- Groundwater flow parameters and data varied within wide ranges in the reviewed aquifer systems. These systems were primarily alluvial in nature rather than other possible depositional settings such as karst limestone for aquifer development.
- Groundwater storage and yield were important factors in water supply for many of the modeled systems. While this observation would appear to be common knowledge, many water supply systems do not utilize groundwater storage but are based on surface water storage.

Analysis of the data ranges supports a framework for decision-making that considers the conjunctive concept and its application in future water management strategies, planning, and program implementation.

Conclusions

Individual model results are important for any region with water concerns about its water. In the larger context of present and future water management, planning, design, implementation, and operations of appropriate management strategies has long-term implications and consequences for any region. While there are many strategies for water management, this study targets conjunctively- and optimally-managed surface water and groundwater through research in four areas of interest. Considered the foundation of conjunctive programs, understanding the physical systems of surface water and groundwater and the interactions and interflows between the surface and subsurface water systems determines the degree of success and long-term viability for water management programs. Programs that manage water systems differing in characteristics, location, and existing infrastructure, can benefit from improved, streamlined management

of their surface water and groundwater sources utilizing conjunctive strategies and optimization.

Conjunctive use of two or more water sources can be thought of as a systematic use and movement of water through “pipes and buckets” or merely an economically-efficient way to divert, transport, and utilize water at demand centers. This simplicity ignores many defining advantages of the overall concept. Understanding a physical water system is best begun within the context of the surrounding watershed, hydrogeology, characteristics, parameters, and interactions. Discussions in this chapter include brief descriptions of a few factors inherent in surface water and groundwater, an example being water flow movement and interactions with the landscape. The results emphasize a similar point about conjunctive use; namely, it is best understood, planned, and implemented within the context of its foundational components and their separate factors. The results of this research define those components as physical water within its natural setting, social drivers, economic considerations, and a legal framework in which any water management strategy works within a certain area. The research separates the four components into basic parameters, potential issues, and unique characteristics and proposes that these major, and associated, factors be considered before making a decision on whether or not to implement a conjunctive management strategy.

This chapter targeted the conjunctive component of physical water systems through analysis and comparison of conjunctive water models, both within each study and across studies. An in-depth evaluation of models with varying aspects of conjunctive use provided information, parameters, and data ranges specific to water systems. It was found that the models were based on mathematical calculations centered on surface

water, groundwater, or an integrated approach. The latter was typically accomplished via application of broad assumptions concerning the less dominant water system, surface water or groundwater.

Optimization approaches also varied through utilization of different criteria and algorithms; each approach, however, revolved around a primary goal or question of the study. Optimization targets ranged from those in interconnected surface water and groundwater systems in which model scenarios minimized groundwater pumping during times of low surface water flows, to economic tradeoff targets in varied model scenarios of different water management operational parameters. Understanding optimization approaches required that the project goal be understood in the context of the physical water setting.

Analysis of parameters and data in each model and comparison across the studies revealed common parameters, similar in nature to those specific in economic-focused models as is discussed in Chapter 3. The analysis generated not only common parameters but also other factors and considerations, indicating the variety of situations in which conjunctive management is applicable and appropriate. Finally, based on the compiled information concerning models and parameters, the evaluation generated a set of data ranges for modeled water systems. The information is subsequently used to prepare a framework for decisions concerning conjunctive management, the topic of Chapter 6.

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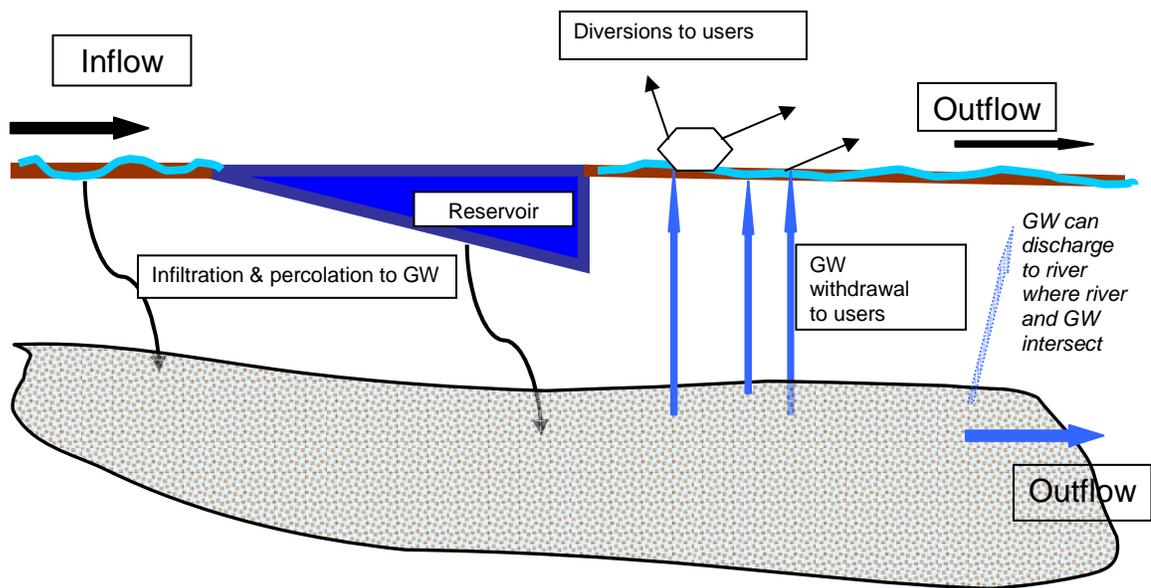


Figure 2.1 "Pipes and Buckets" Diagram of Conjunctive Use

Table 2.1 Selected Water System Models – Summary Information

Reference & Location	Project Goal	Model Description	Optimization Criteria	Major Results
<p>Barker et al. 1983</p> <p>Arkansas River, KN</p>	<p>Model SW-GW interaction in bounded alluvial valley to predict effects of pumping on SW.</p>	<p>Area experienced decline in water levels; therefore, water balance model used to evaluate pumping in shallow unconfined aquifer underlying river. Use of finite-element, 2-D solution for nonlinear flow. Software/code: GW-centric. Model components: GW, SW.</p>	<p>Comparison of historic vs. simulated stream flows with projected variations in GW pumping rates.</p>	<p>Model simulations indicated that periods of low rainfall & less GW recharge were partially offset by major rainfall & increased GW recharge events; increased GW pumping partly offset by increased recharge due to return flows.</p>
<p>Barlow et al. 2003</p> <p>Hunt – Annaquatucket – Pettaquamscutt stream-aquifer system, RI</p>	<p>Create model to evaluate tradeoffs of different water management decisions, primarily between stream depletion and GW pumping.</p>	<p>Modeled stream-aquifer interactions with MODFLOW; simulations to account for physical behavior of system. Maximized GW volume that can be withdrawn for allowable stream depletion during specific months of a year. Software/code: GW-centric. Model components: GW, SW.</p>	<p>Optimization approach replicated management of system. Linear response-matrix: $response = Q[SW\ depletion] / Q[GW\ pumped]\ per\ month$) to combine simulation and optimization models. Included variances in SW & GW withdrawals to model optimal seasonal withdrawals.</p>	<p>Model results indicated that an optimal management scenario would allow 2 additional wells with varied seasonal stream depletion. System could be optimized to increase pumping by 18% and decrease stream depletion by 15%, thereby increasing efficiency of water management in the valley.</p>
<p>Bella et al. 1996</p> <p>Upper Rio Grande basin, southwest U.S.</p>	<p>Use of multi-objective decision techniques to study water allocation conflicts and possible solutions for decision evaluations.</p>	<p>Used 2 multi-objective decision techniques to rank 30 alternative, desired objectives, based on 18 criteria. Software/code: multi-objective decision ranking. Criteria (major components): SW, GW, economic, environment, biologic resources, conjunctive use.</p>	<p>Evaluated the degree of closeness of each alternative to the ideal solution of "no conflict."</p>	<p>Results of numeric decision techniques indicated top-ranked alternative as "meet water quality, protect public interest, construct hydropower, enhance flood control, & reduce sediments." However, grouping alternatives could also reduce deviation from the ideal.</p>

Table 2.1 continued

Reference & Location	Project Goal	Model Description & Components	Optimization Criteria	Major Results
<p>Booker et al. 2005</p> <p>Upper Rio Grande basin, southwest U.S.</p>	<p>Evaluated hydrologic & economic effectiveness of selected drought policy options.</p>	<p>Basin-wide, nonlinear model incorporating hydrologic, economic, and institutional constraints. Model simulates current and future water stress conditions, and the effects of different market conditions. <i>Software/code: SW-centric. Model components: SW, GW, economic, institutional.</i></p>	<p>Comparison of modeled basin inflows to 75% of historic mean.</p>	<p>Model scenario, “no changes,” indicated likelihood of multimillion dollar drought damages when inflows were 50-75% of historic averages. Scenarios with water market transfers indicated reductions in drought costs.</p>
<p>Cai et al. 2003</p> <p>Syr Darya River, Aral Sea basin, central Asia</p>	<p>Integrate hydrologic, agronomic, and economic components in water balance model to study effects of existing vs. optimized water management policies.</p>	<p>Integrated key factors to model a river basin network. Nonlinear program solved with domain decomposition approach. Used model results to analyze effects of policies. <i>Software/code: SW-centric. Model components: SW, GW, agronomic, economic.</i></p>	<p>Short model interval (1 yr) allowed storage effect = 0. Hydrologic, agronomic, and economic subsets were solved using results from previous run (domain decomposition). Economic allocations and optimization assumed individual node demand B/C. Central, optimized water allocations supported.</p>	<p>Baseline vs. optimization modeling results indicated total benefit increase of \$900M using optimized system: average crop yield increases, water withdrawal decreases, flow increases to Aral Sea, and salt discharge decrease. Results also support multi-use of reservoirs for irrigation, hydropower, and downstream ecologic benefits.</p>
<p>Dai & Labadie 2001</p> <p>Arkansas River, CO</p>	<p>Modeling method to integrate SW & GW quantity and quality to evaluate depletion and salinity issues in terms of hydrology, administrative, and legal framework for river basin.</p>	<p>Used MODSIM water accounting model to simulate storage points and links (connecting river reaches, canals, etc.) Method applied to a river basin network. <i>Software/code: GW-centric. Model components: GW, SW, WQ.</i></p>	<p>Optimized using the model program MODSIMQ to minimize costs, weight factors, or water right priorities multiplied by flow rates, per specified river segment.</p>	<p>Simulations: 1) base run with historic water use patterns and no WQ constraints, 2) WQ constraints, and 3) improvements in irrigation efficiency. Results indicate tradeoffs between demand shortages and reduced salinity, with no clear-cut, simple solutions.</p>

Table 2.1 continued

Reference & Location	Project Goal	Model Description & Components	Optimization Criteria	Major Results
<p>Draper et al. 2003</p> <p>Central Valley, Bay area, southern CA</p>	<p>Provide an overview of model processes and incorporation of other models, such as economic inputs and groundwater simulation of the Central Valley.</p>	<p>Overview of utilizing the large scale “economic-engineering optimization model” CALVIN (California value integrated network). The model is supported by inputs from other models (hydrology, facilities, environmental flow constraints, urban & agriculture water values, operating costs) followed by simulated flow gains and losses via USACE’s HEC-PRM. . Software/code: Integrated SW, GW, economic inputs. Model components: SW, GW, economic.</p>	<p>The optimization function targets economic tradeoffs (costs and benefits) as a result of hydraulic water balance of multiple inputs and sub-models. Simulations are solved with HEC-PRM, whereby a network of flow gains and losses are evaluated through a summation process of flows and costs.</p>	<p>Use of CALVIN allows evaluation of water management decision-making options at multi-regional, intertiered scale. Previous models were a mix of results from separate models addressing SW, GW, and economic models for agriculture and urban needs. Data management and documentation is the largest component of the model.</p>
<p>Fleckenstein et al. 2004</p> <p>Cosumnes River, CA</p>	<p>Determine management alternatives to GW overdraft and decreasing river flows; support salmon runs w/ adequate stream flows in the fall.</p>	<p>Two models employed to determine water management options: (1) 1-D channel routing model of vertical seepage (DIFWAVE + Green/Ampt infiltration); (2) use of existing GW model for Sacramento County, based on 3-D finite-element code using IGSM to simulate regional stream-aquifer interaction plus monthly river flows. Software/code: GW-centric. Model components: SW, GW, environmental.</p>	<p>The 1-D routing model was used to estimate a minimum river stage of 18 cm depth, corresponding to a flow target of 0.57m³/s. Model scenarios to restore fall river flows were compared to target.</p>	<p>To reconnect aquifer with stream base flow and promote fall salmon runs, the river system needed 200-300 Mm³/yr recharge, or maintenance of an upstream flow of 1.55 m³/s through reservoir releases. Conjunctive management considered most likely to provide sufficient river flows for short term and support long term restoration of regional GW levels.</p>

Table 2.1 continued

Reference & Location	Project Goal	Model Description & Components	Optimization Criteria	Major Results
<p>Fisher et al. 1995</p> <p>East Bay Municipal Utility District, CA</p>	<p>Evaluate municipal alternatives & costs under drought conditions: demand-reduction strategies & water storage options. Key storage parameter is October carryover target for reservoirs (1.2 x annual demand or use).</p>	<p>Large-scale, water balance model to evaluate least-cost alternatives to address water shortages. System: 2 reservoirs, aqueducts, and treatment to serve 1.1 M people. Model of Mokelumne River flows, storage, use, & releases. Options to increase water supplies – water purchases or conjunctive use program. Software/code: SW-centric. Model components: SW, GW, economic.</p>	<p>Use of operational parameters: "maximum acceptable demand reductions in droughts, storage levels, releases for downstream rights & environmental purposes, transfers/conjunctive use programs."</p>	<p>Two least-cost options tested for urban MUD responses to drought were 1) marketing and 2) adding capacity via a new reservoir. Water marketing via transfers and conjunctive use was lower-cost alternative.</p>
<p>Jenkins et al. 2004</p> <p>Central Valley, Bay area, southern CA</p>	<p>Optimization within large-scale, integrated network model. Data and inputs include SW, GW, system facilities/ capacities, environmental flow constraints, and economic values. Model developed for 3 options: baseline, regional operations, and statewide operations. Model scenarios of economic data show cost/benefits through comparison of results.</p>	<p>Use of the "economic-engineering optimization model" CALVIN (California value integrated network). The model is supported by inputs from other models (hydrology, facilities, environmental flow constraints, urban & agriculture water values, operating costs) & flow gains and losses through USACE's HEC-PRM. Model was run for (1) water scarcity vs. cost, (2) reservoir & conveyance expansion, (3) willingness to pay, (4) environmental regulation, (5) conjunctive use, (6) water transfers. Software/code: Integrated SW, GW, economic inputs. Model components: SW, GW, economic, environmental.</p>	<p>The optimization function targets economic tradeoffs (costs and benefits) as a result of hydraulic water balance of multiple inputs and sub-models. Simulations are solved with HEC-PRM, whereby a network of flow gains and losses are evaluated through a summation process of flows and costs.</p>	<p>Results: (1) regional and statewide water markets can reduce water scarcity costs >80% over baseline costs. (2) Conveyance expansion costs less than reservoir expansion, due to higher economic values of GW storage. (3) Willingness to pay varies with water and demand conditions. (4) Under regional/state market conditions, environmental flows appear to have little impact on agriculture and urban users. (5) Regional markets tend to employ GW more efficiently. (6) Model suggest small changes in allocations, conjunctive use, and more flexible operations all support economic improvements in state water mgt. Study also noted model limitations of varying data quality, system simplification, and non-inclusion of certain factors (hydropower).</p>

Table 2.1 continued				
Reference & Location	Project Goal	Model Description & Components	Optimization Criteria	Major Results
<p>Peranginangin et al. 2004</p> <p>Singkarak-Ombilin basin, West Sumatra Province, Indonesia</p>	<p>Diversions from primary lake in the basin decreased available water 81-95%. Water accounting model to evaluate water use under water-stress conditions.</p>	<p>Modify Molden & Sakthivadivel (1999) model to separate SW and GW components; apply water balance modeling via Thornthwaite-Mather model to evaluate water uses and patterns in basin. Software/code: SW-centric. Model components: SW, GW.</p>	<p>Evaluate results of SW, GW use scenarios against beneficial v. non-beneficial water depletions, resulting in predicted changes in available SW & GW.</p>	<p>Model demonstrates that conjunctive use can be used to 1) recharge GW during rainy season by expanding irrigation field area to allow excess water to infiltrate/percolate, and 2) extend SW supplies during dry months by pumping from shallow aquifer.</p>
<p>Pulido-Velazquez et al. 2004</p> <p>Central Valley, Bay area, southern CA</p>	<p>Use of CALVIN's simulations of conjunctive use scenarios for southern California to evaluate: 1) baseline; 2) economic drivers without institutional constraints; 3) scenario 2 with new conjunctive use facilities. Model applied to 8 urban and 3 agricultural demand centers.</p>	<p>Use of "economic-engineering optimization model" CALVIN (California value integrated network). The model allows inputs results of other models (hydrology, facilities, environmental flow constraints, urban & agriculture water values, operating costs), then simulates flow gains and losses through USACE's HEC-PRM. Software/code: Integrated SW, GW, economic inputs. Model components: SW, GW, economic.</p>	<p>The optimization function targets economic tradeoffs (costs and benefits) as a result of hydraulic water balance of multiple inputs and sub-models. Simulations are solved with HEC-PRM, whereby a network of flow gains and losses are evaluated through summation of flows and costs.</p>	<p>Model results indicate the following: Flexible water allocations (e.g. water markets) with improvements in conjunctive use systems can reduce scarcity and its costs. The researched conjunctive use projects could generate net benefits in the range of \$98M/year. Flexible markets and conjunctive operations can reduce need for SW imports. The model can provide insights as to system operating rules. Highest value for storage expansion is in areas of high WQ and power.</p>
<p>Rao et al. 2004</p> <p>East coast, India</p>	<p>Develop 2 scenarios for regional model for deltaic aquifer system with irrigation: 1) Minimize supply costs & supply SW, GW at demand centers; 2) maximize, or conserve, GW storage in space & time.</p>	<p>Theoretical modeling approach for water demands & allocations. Flow model: SHARP interface with artificial neural networks. Management / optimization decisions: simulation annealing code. Software/code: SW-centric. Model components: SW, GW, economic.</p>	<p>Model manages water demands in time, space through optimal allocation of SW & GW. Use of simulated annealing code for decision points.</p>	<p>Modeling approach intended for use at macro-level planning of brackish, deltaic regions of irrigation. Allocation of SW, GW in time and space can be determined through application of simulated annealing code.</p>

Table 2.1 continued				
Reference & Location	Project Goal	Model Description & Components	Optimization Criteria	Major Results
<p>Reichard 1995</p> <p>Santa Clara-Calleguas basin, CA</p>	<p>Model effects of pumping on existing conjunctive system. SW management expressed as accessing river water within water rights restrictions. Water quality issues (seawater intrusion) addressed through additional GW supplied to subsurface to control chloride gradients.</p>	<p>Model based on previous CA DWR model. Five aquifers grouped as 2 layers; assumed low vertical hydraulic conductivity except in artificial recharge area. Drains, artificial recharge, production wells included. Model evaluated SW diversions by probability distribution. Comparison of deterministic vs. stochastic approaches.</p> <p>Software/code: Integrated SW, GW inputs. Model components: SW, GW.</p>	<p>Optimization decisions: 1) minimize supplemental water 2) minimize water use reductions; or 3) minimize changes from current pumping. Evaluated the reliability of optimization results using Monte Carlo analysis.</p>	<p>Simulation method of using river diversions as probability distribution allowed identification of optimal values for selected decision variables. Simulation results indicated control of seawater intrusion would require significant decrease in water use to allow GW to stay in subsurface system, or decrease in GW pumping to decrease gradient-driven intrusion, or acquisition of additional SW supply for artificial recharge.</p>
<p>Yang et al. 2001</p> <p>River Shiyang basin, NW China</p>	<p>Evaluate benefits of water use vs. GW mining, saline soils, & spring disappearance. Multi-objective, weighted function model to evaluate trade-offs between desired objectives of water supply, WQ, economics, and environmental factors.</p>	<p>Use multi-objective model of major drivers in basin to minimize conflicts between objectives. Primary objectives: 1) meet water supply needs short and long term, 2) conjunctively manage SW/GW, 3) minimize WQ degradation, 4) meet increases in water demands by various users, 5) achieve best values of water use. Software/code: multi-objective decision ranking. Model components: SW, GW, WQ, economic, environmental.</p>	<p>"Multi-objective optimization": Optimize water use alternative scenarios through recognition of tradeoffs & minimization of conflicts between desired objectives. Use of weighted functions to demonstrate constraint objectives.</p>	<p>Optimized water use scenarios indicated that water demands of industry, forestry, human uses could be met. However, environmental and economic water uses showed water deficit. No final solution indicated resolution of overall water deficit, therefore suggested actions include SW importation and water conservation measures.</p>

Notes: B/C – benefits and costs
 GW – groundwater
 Mm³/y – million cubic meters per year
 Q – flow rate (positive for SW; negative for GW pumping)
 SW – surface water
 WQ – water quality

Table 2.2 Parameters and Other Considerations

Commonly Identified Parameters			
Inflows		Outflows	
Surface Water	Groundwater	Surface Water	Groundwater
• Upstream flows (15)	• Recharge as lateral inflow (5)	• Consumptive use (15)	• Pumping rates (6)
• Reservoir storage and discharge (9)	• Leakage from river system (infiltration or vertical recharge) (8)	• Downstream flows (15)	• Aquifer outflow (5)
• Return flows (5)	• Deep percolation into aquifer (vertical recharge) (5)	• Diversions or canals (10)	• Leakage to river (3)
	• Artificial recharge of unconfined, shallow aquifer (5)	• Evaporation / evapotranspiration (4)	• Water table evaporation (5)
		• Seepage (8)	
		• Percolation (5)	
Other Factors			
Land / Water Uses	Benefits	Costs	Legal / Institutional Impacts
Water supply	Water uses	Water supply	Regulatory controls
Irrigated agriculture	Agricultural profits	Groundwater pumping	Treaty/compact water allocation requirements
Fish hatchery	Municipal	Water conveyance	Environmental flows or habitat requirements
Forestry	Industry	Irrigation efficiency	Water conservation rules
Recreation	Rural	Municipal	
Reservoir site	Hydropower	Industry	
Natural lake	Ecological		
Surface water-groundwater flux	Incentives:		
Water quality	- <i>Taxes</i>		
Riverbed degradation	- <i>Subsidies</i>		
Water-logged soil	- <i>Water market</i>		
Fresh/saltwater interface			

Note: Numbers in parentheses denote number of reviewed models that described the parameter out of 15 models.

Table 2.3 Data Ranges in Selected Water System Models

Study Area Background			
Data Set	Low Range	High Range	Unit
Study locations	Syr Darya, Aral Sea (1); Arkansas R. (2); Central Valley, CA (4); China (1); east India (1); W. Sumatra, Indonesia (1); Rio Grande (2)		
Records of historic flow data	6	> 100	years
Area of study	49	8,784	km ²
Area of basin	up to 30,000		km ²
Regional precipitation	10 - 25	120 - 290	cm / yr
Water uses in modeled system: Predominant - agriculture, municipal/urban, flood control. Other: environmental, fish hatcheries, hydropower, domestic, livestock, coal washing plants, thermal power plants, forestry			
Surface Water (SW) Systems			
Data Set	Low Range	High Range	Unit
Number of rivers/streams	1	>20	
Average flow rate	0	2,650	m ³ /s
Infiltration	0.59	0.74	m ³ /s
Stream-aquifer connectivity	12 of 15		reported
Groundwater (GW) Systems			
Data Set	Low Range	High Range	Unit
Number of GW basins	1	>28	
Recharge	0.03	250,000	m ³ /s
Saturated thickness	0	200	m
Hydraulic conductivity *	61	243	m/d
Transmissivity	10	6,000	m ² /d
Specific yield	0.1	0.3	[dimensionless]
Storage coefficient	10 ⁻⁴	10 ⁻¹	[dimensionless]
Water table evaporation occurs	5 of 12		
Pumping yields	0.006	10.2	m ³ /s
Total annual pumping	1.92	703	Mm ³ / yr
Total average pumping rate per number of wells:			3 public supply; others are irrigation wells
	22 - 80 Mm ³ / yr	89 – 160 wells	
	1.92 Mm ³ / yr	18 wells	14 public supply wells 1 industry well 3 fish hatchery wells
	703 Mm ³ / yr	33 wells	Irrigation & public supply
	937 Mm ³ / yr	> 10,700 wells	Irrigation wells
Explicit Aquifer Characteristics			
Shallow, unconfined			9 of 12
Shallow unconfined overlying confined aquifer			5 of 12
Alluvial deposition			9 of 12
Bedrock or fault - bounded			2 of 12
Multi-layer aquifer system			5 of 12

* Models typically did not differentiate into lateral and vertical components

CHAPTER 3

RE-VALUING CONJUNCTIVE USE AND ECONOMIC PARAMETERS

Introduction

Conjunctive use, a water management strategy that utilizes distinct surface water and groundwater characteristics has been recognized and applied since the 1950's. Also known as conjunctive management, it is a fairly uncomplicated concept, technically feasible, and with a record of long-term programs implemented in semiarid regions. Many publications have documented significant findings in theoretical and applied studies related to the economics underlying conjunctive use, as well as efficient resource use through optimization targets and modeling. It is more often utilized in semiarid regions subject to drought, an example being the agricultural regions of central California, rather than regions of higher rainfall or which contain multiple tributaries to major rivers such as found along the eastern U.S. coast. While studies have focused on the underlying economic mechanisms of conjunctive use, few have focused on basic factors that support successful conjunctive management programs. Based on these considerations, conjunctive use is surprisingly less known and utilized in some regions than might otherwise be anticipated across the western United States. Some states, California, Arizona, and Colorado, for example, have extensive conjunctive use

programs, while others such as Texas have considered the option but do not tend to create state-based programs.

Due to increases in population, recurring droughts, allocations to agriculture and urban water demands, and other stresses on natural resources, there is a growing interest in current and future water management (Rijsberman, 2009; Circle of Blue, 2009).

Approaches that worked well in previous decades may not be the best strategies under current and future conditions. An example is dam building in the 1930's. The boom was predicated on conditions of fewer metropolitan centers, smaller acreage of irrigated lands, and far less energy consumption than is now enjoyed. Whereas in the 1930's many major rivers did not have dams and reservoirs, today it is a rare river that runs freely without dams. Conjunctive use offers flexible water management through groundwater storage in addition to utilization of existing surface water management systems to address multiple aspects of these water stresses and challenges.

An evaluation of conjunctive use studies in the literature indicates four major factors in its successful application – technical feasibility of utilizing available physical water systems, economics, water laws, and society's input applicable to the water management region. This paper discusses conjunctive use and the role of economics and evaluates significant parameters in conjunctive strategies. An evaluation of parameters employed in both theoretical and applied economic evaluations of conjunctive use models is made. The purpose of the study is to identify and simplify basic parameters necessary for planning and implementation of future conjunctive use programs, regardless of location, as well parameters unique to certain models and studies. The

results are discussed in light of considerations that water managers and planners may learn from successful programs.

Understanding Conjunctive Use

Simply stated, conjunctive use is the optimized utilization of water sources over time when more than one water source is simultaneously available. In theory, it is straightforward to use one water source while allowing another source to be conserved, stored, or allowed to replenish. In reality, optimization of surface water and groundwater can be difficult to implement as a practice, particularly when other water management tools have been in place for years. In such regions, water management may not be questioned until external conditions have changed and forced the question of whether the current strategy is viable for the present and future. Conjunctive use also has physical water system limitations as discussed in Chapter 2.

Overall, the balance between benefits and costs to a water supply region should be considered in water management strategies. Conjunctive use for water management has been recommended in research and policy documents (NWRI, 1998; Texas Senate Select Committee on Water Policy, 2004). Definitive methods for implementation, however, are rarely included in such documents, indicating a lack of knowledge and/or agreement on which scientific, economic, and political factors determine whether or not conjunctive management is a viable water management strategy.

Adding to a common idea that conjunctive use is rather vague, almost every publication provides a definition aligned with the specific goals and focus of the study being discussed. While a flexible approach to understanding conjunctive use is important in getting projects to the planning stage, variations in understanding, technical

approaches, and goals can add to general confusion about its applicability. To illustrate the differences in conjunctive use terminology, selected definitions follow:

I. Economic-based studies:

- “Since surface waters can be highly variable from one year to the next, aquifers also function as a natural inventory system for smoothing annual fluctuations in surface flows.” (Knapp and Olson, 1995)
- “... [C]onjunctive use refers to the practice of coordinating the use of surface water and groundwater resources during periods of water scarcity and surplus.” (Schuck and Green, 2003)

II. Hydrologic/hydrogeologic studies:

- “Successful conjunctive use is defined here as a water resource system where (1) surface water and groundwater users have reasonable access to the water, and (2) no wells are summarily shut down.” (NGWA, 2007)
- “Conjunctive water use refers to simultaneous use of surface water and groundwater to meet crop demand... Conjunctive management, by contrast, refers to efforts planned at the scheme and basin levels to optimize productivity, equity, and environmental sustainability by simultaneously managing surface and groundwater resources.” (World Bank, 2006)
- “In basins approaching full development of water resources, optimal beneficial use can be obtained by conjunctive use, which involves the coordinated and planned operation of both surface water and groundwater

resources to meet water requirements in a manner whereby water is conserved.” (Todd and Mays, 2005)

For the purposes of this research, the definition of conjunctive use is simplified as follows: *the optimized and economically efficient use of surface water and groundwater supplies, such that one source allays the temporal or spatial shortcomings of another source through additional use options or storage.* Optimization of water supplies may be achieved through models to realize such goals as water supply distribution, storage, and/or economic targets.

Overview of Surface Water and Groundwater Systems

Conjunctive use strategy takes advantage of major factors in the hydrologic cycle, well described in many textbooks, an example being Todd and Mays (2005). Surface and ground water can move at greatly different rates, and their storage is dissimilar in nature. Surface waters in streams and rivers tend to move quickly and can be measured in seconds and minutes (Dingman, 2002). Natural replenishment in the system takes place through rainfall events, similarly measured, and may occur in many locations within a river’s watershed over the course of the annual cycle. Over years of developing water transport systems, civilizations have found that surface water sources are more accessible for use and diversion. Infrastructure for surface water storage and use reflects this base of knowledge characterized by the building of extensive dams, reservoirs, canals, and pipelines. Groundwater, however, is dependent on the geologic matrix through which it moves. Thus, groundwater flow rates can vary from minutes to years to decades (Todd and Mays, 2005). Aquifers recharge through precipitation, percolation, and the

downward migration of water. Groundwater storage occurs in various regions of the aquifer over time, reflecting differences in surface and subsurface geologies.

Where surface water and groundwater are both available, conjunctive management can utilize the advantages of their different characteristics of these two primary water sources. Research studies about the physical systems of conjunctive use evaluated these characteristics from different views. Makroon and Burges (1978) conducted a systems analysis; Reichard and Raucher (2003) evaluated conjunctive use through hydrologic and economic approaches, including program baselines and cost-benefit analysis. Additionally, program implementation can be designed to take advantage of seasonal surface water variability and naturally stored groundwater. Surface water is the primary water source in most cases, being cheaper and more accessible than groundwater due to its proximity to water users, in-place infrastructure, and legal framework developed over time. Through irrigation districts or state water agencies, or a combination of the two, water is allocated to irrigated agriculture, municipalities, rural users, and industry. Should groundwater be available within an effective pumping depth and distance from wells to distribution systems, and also be permitted, then water suppliers may then opt to utilize pumped groundwater in times of low surface water flows and low rainfall.

Just as important as the efficient use of water is the interaction between surface water bodies and groundwater. Interactions may have been known, but were often considered negligible in water resource planning models. With the advent of measurable drawdown of surface water due to groundwater pumping, however, interactions have become more important in defining water rights and modeling water availability

scenarios. Some models include the connections and flow interactions as well as the separate flow characteristics of surface water vs. groundwater systems. The surface water-groundwater flow interactions are key to understanding potential impacts of reductions and increases in either source of water. Conjunctive use models can include quantifiable interactions in water balance and availability modeling, thereby addressing questions of how various water balance scenarios might affect physical water and ecologic systems, as well as generating data on the possible benefits of long-term optimization of each source of water.

Role of Economics

The characteristics of conjunctive use systems are varied and changing, based on a demand-management approach. As discussed in a following section, the economic evaluation may be demand- or supply-based. Regardless, one critical role in determining a water management strategy is whether the approach can be considered efficient and, if so, through what economic mechanisms. When viewed as a “renewable but depletable” natural resource, water allocations begin with a separation of the economic considerations in surface water and groundwater uses (Tietenberg, 2003). In general, surface water allocations take competing, concurrent, and future uses into account, as well as anticipated variations in flow volumes. Groundwater allocations may run into issues typical of depletable natural resources. In contrast, surface water is considered replenishable, although the water volume replenished to the system can be greatly reduced and doubtful of timing during drought periods. With theoretically efficient systems, surface water allocations will allow equalization of marginal net benefits for all water users, and trades between high and low value uses. On the other hand, efficient use

of groundwater may be less affected by variations in volume and more affected by opportunity costs, as the water pumped in real time may not appreciably be noted until some future date.

Conjunctive use as a water strategy was initially focused on the economic advantages inherent in groundwater storage (Banks, 1953). Interest and research in the strategy has grown over time, with probable economic factors, positive and negative, that affect conjunctive use programs being subsequently assessed (Clendenen, 1955; Todd, 1959). Programming techniques assessed the design and operations for joint operation of a surface reservoir and aquifer in agricultural applications and also explored the economic viability of this management approach (Buras, 1963). Groundwater valuations were based on stochastic modeling of an “optimal inventory policy for ground water,” where 5-year intervals of computations for optimal water use were founded on the stock of available groundwater. The results firmly identified conjunctive use as a viable water management strategy (Burt, 1964). Prior to the advent of powerful computational tools, conjunctive use was also analyzed in terms of systems and levels of associated issues (Maknoon and Burges, 1978) and optimization of operations and controls for agricultural and urban water uses (Noel et al., 1980).

Studies of conjunctive use continued to focus on economic analysis and agricultural efficiency for several decades (Gisser and Sanchez, 1980; Feinerman, 1988). Tsur and Graham-Tomasi (1991) and Provencher and Burt (1993) evaluated optimal groundwater use with stochastic surface water supplies through user decision rules. Knapp and Olson (1995) conducted a similar evaluation but included artificial recharge as an additional economic consideration in Kern County, California, to assess the

empirical aspects of their model. With continued improvements in computers and software design and power as well as user access, conjunctive use research incorporated large data sets in numerical models for basin-scale water availability and resource management decisions, thereby enabling more efficient decisions on water supplies allocated towards varied seasonal water demand for urban and agricultural uses. Economic analysis continues to play a vital part in assessing whether a conjunctive program is appropriate for a specific region.

Benefits and Costs

The baseline for conjunctive use in economic theory is the efficient use of water, regardless of water source (surface water or groundwater). Benefits expected from conjunctive use programs were recognized by Clendenen (1955) and updated in Todd and Mays (2005). These observations included development in stages, integration with existing facilities, potential to increase water conservation, reduced surface water storage with increased groundwater use and therefore reduced evaporation losses, and timed water releases for multiple water demands. Some of the identified costs or disadvantages are increased power consumption through groundwater pumping and conveyance, the possibility of increased water salinities, and more difficult cost allocations. A thorough review of procedures to apply the related valuations necessary in water balance models was presented by McKinney et al. (1999).

An example of desired goals and benefits of conjunctive use is found with the California Department of Water Resources (CDWR)'s Conjunctive Water Management Branch (CWMB). The CWMB program supports groundwater basins that request planning assistance and funding through competitive grants (CDWR, 2009). In

partnering with 24 local agencies since 2000, the program has allocated \$30 million from a state water bond and \$7 million under the Local Groundwater Management Assistance Act. Linking between programs is the CWMB mission: “Through the coordinated optimization of surface and groundwater supplies, California can increase its water supply reliability and water supply system flexibility, and reduce dry year demand deficit, overdraft, and subsidence” (CDWR, 2009). The program emphasis on groundwater, rather than surface water in the program, results from decades of surface water management, whereas groundwater has not received as much regulation.

Each basin has specific water needs, constraints, and stakeholder concerns. A review of partnerships on the website indicated several major, common goals, including reduction of groundwater overdraft, meeting increased water demands, development of recharge and storage in the basin, and identification of potential conjunctive use projects. The success of the CWMB program is the increasing number of partnerships over the years, allocating funds through a competitive grant process, and the realization of more efficiently managing groundwater supplies at the basin level. In other words, two additional benefits are management-driven benefits at the level of groundwater use, rather than at the level of the state, but also pooled and therefore more efficient funding at the state level awarded at the regional level through competition.

Methods

Economic and water balance models can be sources of information as well as predictive analytical tools. As its foundation, a model includes algorithms appropriate to the model’s question or target, parameters to allow logical and quantitative evaluation of the question, and data sets that fit the parameters. Economic models with conjunctive

management applications are no different. Theoretical or applied, the model is developed to explore an aspect of efficient surface water and groundwater supply, storage, and utilization.

Analysis of Economic-Conjunctive Use Parameters

The research question and approach focused on significant economic parameters of conjunctive management. Models that evaluated economic theory, and water balance models with economic applications, were analyzed for common, shared parameters. The models were also examined for unique parameters that provide insights into economically viable conjunctive management. This assessment did not include conjunctive use models that focused on water balance and availability (see Chapter 2), unless an economic focus was part of the model.

First, based on a demonstration or proof of economic efficiency in conjunctive use, models were chosen for analysis of their parameters. More models have been developed than were reviewed in this analysis; however, selected models demonstrated significant features of economic viability and conjunctive use. Some models were the first in a line of economic proofs. Others built on prior models to better develop an aspect of economics in conjunctive use. “Applied” models employed economic theory in specific regions and programs of conjunctive use. During model selection, an understanding of the research objectives, model approach, and explicit assumptions provided significant information for the initial assessment.

Parameters common to the majority were evaluated through comparison and repetition. Over the years, authors tended to use different terminology to distinguish or emphasize their methodologies towards a research goal. Where applicable, therefore,

some terms for parameters have been chosen for this analysis that are close to, but not the original, terms used in a previous study. Through a process of comparison, grouping, and elimination, selected models were evaluated for parameters shared by the majority of reviewed models. Economic data as provided were also examined but found to be so specific with regard to spatial and timeframe references such that it was not possible to ascertain data ranges meaningful to general conjunctive use.

Finally, through the parameter evaluation and comparison, a description of parameters unique to the success of a conjunctive use strategy was generated. Thus the goal of this analysis, which was to better define economic factors that support conjunctive use strategies, was satisfied through analysis and compilation of research from existing models.

Results and Discussion

Model Overview

Twelve models related to conjunctive use and economics are summarized in Table 3.1. The models were referenced by citation and location. Objectives and model descriptions were categorized by the research approach, here succinctly described as “theoretical,” theoretical-empirical,” and “applied.” Economic theory tested through specific proofs/theorems, for example, was at the heart of the Provencher and Burt (1993) study that analyzed risk externalities in conjunctive use programs. Studies that first established applicable economic theory and algorithms for the questions of interest, and tested the projected results with data from a specific region or conjunctive use program, were described as “theoretical-empirical” models. Examples are the models of Bredehoeft and Young (1988), Knapp and Olson (1995), and Schuck and Green (2002;

2003). Since the advent of more powerful numerical modeling, linear algorithms have largely been replaced with applied models that draw on a variety of software and integration of physical (surface water and groundwater), economic, and agricultural data sets. Excellent examples of “applied,” integrated models employed as research tools were noted in Booker et al. (2005) and Cai et al. (2003). The former evaluated drought effects on water policies in the Upper Rio Grande Basin, while the second provided an integrated “hydrologic-agronomic-economic model” for assessing current versus optimal conditions in the Syr Darya River catchment of the Aral Sea basin.

Although the models were not selected on the basis of locations, a review of the models’ general watershed and major water users was informative. The water systems for which the models were developed are located in different countries (Asia, Australia, Israel, Nigeria, and states in the western United States). The common factor was increasing water demands on available surface water supplies. Another factor was the relationship between relatively low surface water supply and seasonal variations in aquifer levels, indicating a water-stressed area rather than a semi-arid one. The predominant water use in these models was agriculture, not surprising in terms of the volume of water necessary to grow sufficient to high crop yields. Other major users – urban, recreational, or environmental – were included in models created after the mid-1990’s, mainly a result of greater computing power and larger, available data sets.

The objectives of each body of research were also enlightening. Though the tool of economic modeling was common, the goals were different. Ranging from the valuation of groundwater under different conditions, to modeling supply-based water prices and assessing water delivery efficiency, each model was, as might be expected, an

independent body of research focused on very different research questions. The results, however, as summarized in Table 3.1 under “Policy Implications,” consistently illustrate the efficiency of conjunctive use, the value of groundwater as an economic buffer and storage option to “smooth out fluctuations” in variable surface water supplies (Knapp and Olson, 1995), and the potential for conjunctive use in future programs involving water conservation and environmental flow targets. Research studies and this analysis demonstrate that conjunctive management programs offer positive benefits which are not necessarily included in discussions concerning water management strategies for the future.

Common Parameters

Parameters provide a critical form of implementing the goals, targets, and paths towards possible outcomes of modeling. What data go into a model, obviously have defining roles on the model results. In situations of conjunctive use, model inputs are even more important as the models can be quite different from each other, not only in physical characteristics, timing of model development and therefore access to increasingly more powerful and integrated software, but also in quantitatively finding a path to answer relevant questions. Thus, a portion of this study defines parameters common to conjunctive use models. While other parameters also are used in models, those discussed in this analysis are common across different studies, geographic locations, and program goals.

Common model parameters are listed in Table 3.2. They are grouped as physical and economic characteristics. The common parameters are separated into characteristics distinctive of surface water, groundwater, agriculture, and “other.” The latter two

categories are included because many economic models of conjunctive use focus on agriculture and irrigation water demands.

Physical characteristics are those that can be directly quantified or measured. Surface water inflows are typically quantified through flow rate or flow volume measurements at hydrologic gauges upstream of the study area. Other inflows can be return flows from irrigated areas to the stream or shallow groundwater that moves into the streamflow. Common surface water “losses” in the models include measurable diversions, required downstream flows, evaporation, and surface water infiltration or percolation to the subsurface.

Due to the complexity inherent in detailed groundwater models, the reviewed economic models of conjunctive use systems reviewed herein most often used the “single tank” approach (Bear, 1977). This simplifies an aquifer to a tank with an inlet and outlet pipe, and uses hydraulic head, or groundwater levels, as measurement of changes in the aquifer. Groundwater inflows are the volume of available groundwater and recharge rates. Unless a specific discharge area such as a large spring is included in the model, groundwater outflows are often not included. Areas of the study limits, irrigated lands, and aquifer aid in physically constraining the model. As a measurement of available groundwater, some models included specific yield for unconfined or water table aquifers, or the storage coefficient in the case of confined or aquifer systems under greater than ambient pressure.

Economic parameters focus around valuation or costs of the physical parameters. The valuations are tied into data of the research question. Physical data are used to prepare assessment parameters such as the marginal costs of surface water and

groundwater. To assess marginal costs, costs of surface water (withdrawal, conveyance, drainage collection and disposal) are routinely employed to assess marginal costs, along with the costs of groundwater pumping at depths, energy costs and occasionally, the cost of artificial recharge. For agriculture, crop-specific production costs and revenue are common to the models. Other common parameters relate to model time periods and discount rates for valuations.

A conservative note about Table 3.2 should be considered with regard to the list of parameters commonly used in economic modeling of conjunctive use systems. Many more quantifiable parameters exist for stream reaches, aquifers, and agriculture crop production than are included in some economic models or in this study. For example, any stream reach has a number of parameters significant to understanding its hydrology within a larger watershed, including channel width, depth and roughness (Manning's) coefficient, all of which affect flows over time; the number and volume of diversions that change with the number of water rights or allocated flows to different users; variations in stream flows over time; and changes in water demands and uses over the years. The few groundwater parameters in Table 3.2 should not be taken as an indication that aquifer systems are thoroughly represented with the six listed parameters. Rather, aquifers tend to be complex, multi-layered, and dependent upon the depositional history of the geologic matrix comprising the aquifer. Quite a few more parameters and data sets than shown in Table 3.2 are necessary to create a representative model of an aquifer. Why are more common parameters not shared among the economic models? Most likely, the observation reflects the fact that no model can represent a real system with 100 percent accuracy. At the foundation of a model, algorithms, parameters, and assumptions must

be sufficiently close to reality so as to sufficiently and accurately address the research question, which requires different levels of specificity. In the reviewed economic models, valuations are assumed to be close enough to reality by utilizing the common parameters, as well as those unique to the study question. The following section therefore targets these unique parameters.

Parameters Unique to Conjunctive Use

That conjunctive use has been successful in certain regions is certainly due to strengths and distinctive features in socio-economic conditions as well as physical surface water and aquifer characteristics. To better determine those unique parameters, the same selection of research models is examined, and the results placed in Table 3.3. As previously mentioned, models seek to adequately reflect the conditions under which the research question is placed. To understand the relevance of the parameters, it is necessary to review the technical approach to the modeling effort and the associated assumptions. Table 3.3 supplements the information provided in Table 3.1, allowing a more rounded understanding of the research.

The models utilize agricultural, economic, hydrology, and hydrogeology components to different degrees of input, but all include at least some identification of these factors. Every model takes a different approach via the choice of algorithms and/or software to best address the research focus. Under “Model Approach,” therefore, a review of the models and valuations informs in regard to linear and dynamic programming, valuation approaches, and incorporation of additional factors such as the impact of surface water rights on estimations of water availability.

Whether implicit or explicit, assumptions impart limits and constraints on a model. The third column of Table 3.3 lists assumptions explicitly identified in the research publication. Some publications provide detailed assumptions, while others are not. Some assumptions are found in more than one model, but none can be considered “common” to the group, due primarily to the technical framework of the model. In all cases, the assumptions help one understand how the technical approach in the model is constrained.

Unique parameters per model are listed in the right-hand column of Table 3.3. Based on comparison and evaluation of common parameters, these are the parameters incorporated by individual studies. These are notable parameters rather than model results or projections and are appropriately grouped as follows:

I. Groundwater-focused parameters are:

- Changes in groundwater levels as a measure of social welfare valuation
- Groundwater valuation as usage cost for individuals versus a central agency
- Groundwater valuation as buffer to varying surface water supplies
- Groundwater sub-unit valuations as input to water management policy options
- Changes in groundwater storage used to estimate supply-based, surface water scarcity values
- Well capacity versus income and its variance, to approximate risk aversion to unexpected changes in surface water flows

II. Surface water-focused parameters are:

- Variable surface water flows to incorporate externalities of water laws, institutional allocations, hydropower, recreation

- For interconnected surface and ground water system, value surface water scarcity through effects of upstream groundwater pumping
- Marginal willingness-to-pay by water users
- Surface water price as control on volume of water use

III. System-focused parameters are:

- Water use valuations by sector (agriculture, urban, hydropower, recreation)
- Operational costs and benefits

The differences in these unique parameters highlight the flexibility of conjunctive use as a water management strategy, groundwater as a stabilizing factor in varying surface water supplies, and the effects of externalities. They also underscore a fundamental benefit of conjunctive use, namely, its applicability to diverse regions and water management issues, within the context of the region's surface water and groundwater characteristics. External costs are always a factor and are best considered within the same regional context.

Implications for Future Conjunctive Use Programs

The benefit of identifying common parameters is relevant to planning and initial development of conjunctive use programs. The parameters in Table 3.2 provide a starting point for decision-makers and stakeholders to identify probable conjunctive use economics in a particular water management area, and to work from that point onwards toward a potential program to increase the efficiency of current and future water use. Unique parameters also help identify those factors not necessarily in the planning mainstream but which may be critical to viable future water management.

The groundwater-focused parameters in Table 3.3 provide a base for economic evaluation of various storage and retrieval options and economic considerations. Conversely, a hydraulically connected stream and shallow aquifer is not appropriate for groundwater storage (unless a deeper aquifer, not vertically connected to the shallow system, was considered suitable). However, the parameter identified in Table 3.3 for this situation points out the need for economic valuation of depleted downstream flows, particularly if the upstream water users are permitted to pump groundwater. Deliberation of future water management options, therefore, is an excellent basis for economic evaluation of conjunctive use through the identified parameters and associated models.

Conclusions

The determination of common and unique parameters allows compilation of a source of information for economic evaluations of conjunctive use programs in the planning stages. No such list of parameters currently exists, primarily because researchers and program managers typically focus on research goals, approaches, technical constraints, variables, and issues that inform their specific study. The current state of water management in the southwestern United States includes concerns of water supplies not meeting future water demands, and considerations regarding alternative solutions. Conjunctive use, while better established in some regions than others, is rarely noted by non-technical stakeholders and decision-makers. However, the capability of conjunctive use programs, with their viability and flexibility under varying conditions to efficiently manage water supply, make future conjunctive use a worthwhile option for evaluation by regional water management teams. This research reviews the notable economic research studies and models over the years that clearly illustrate the economic

efficacy of conjunctive use, and notes the success of recent programs in California.

Using published models, an in-depth analysis and comparison of model goals, technical approach, assumptions, and parameters used allows determination of commonly-shared, as well as unique, economic parameters. These parameters can be utilized in economic evaluations of potential conjunctive use programs for specific regions. The common and unique parameters are also utilized in a separate body of research, constructing a guidance document concerning conjunctive use for decision-makers and stakeholders.

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Table 3.1 Overview of Selected Models

Reference	Location	Objective	Model Description	Water Users	Policy Implications
Acharya & Barbier, 2000	Northern Nigeria	Value changes in GW recharge on social welfare, and therefore changes in regional ecosystem.	<u>Theoretical - empirical</u> : Uses production of specific crops to value GW recharge. Changes in GW levels are then used to derive welfare effects on farmers.	Agriculture	GW recharge is of high value to wetland crop production. When so valued, dams and other SW diversions may not be the most efficient water management option for farmland.
Booker et al., 2005	Upper Rio Grande basin, southwest U.S.	Integrate hydrology and economic to model effectiveness of institutional drought policy options on water systems and economic benefits/costs.	<u>Applied</u> : Basinwide, nonlinear model incorporates hydrologic, economic, legal, and institutional limits on policy decisions. Optimization utilizes water flows or benefits to test drought policies. Alternative option tests water markets within interstate treaty constraints.	Agriculture (IDs), urban (municipal and industrial), recreation	Drought damage costs may be ~\$100/acre-foot of water supply reductions, when SW flows decrease below ½ of long term averages. Model demonstrates that water markets within the basin may reduce damages and limit GW overdrafts, likely in most droughts.
Bredehoeft & Young, 1988	South Platte River, CO	Evaluate the way irrigators maximize their profits and stabilize income through choice of water source, SW or GW or both.	<u>Theoretical - empirical</u> : Build on 1972 simulation of hydrology and economics to include risk aversion. Simulate decisions to install wells, thereby maximizing income & avoiding risk of low SW via more expensive option of pumping. Study area is same as that in 1972; 3 subareas are modeled to vary GW pumping capacity.	Agriculture	Each decision to divert SW and/or pump GW reduces the amount of stream flow available in responsive stream-aquifer systems. Maximize GW pumping to available acreage greatly increases economic benefits to be derived, and reduces variance in expected income to “almost 0.”

Table 3.1 continued

Cai et al., 2003	Syr Darya River, Aral Sea basin, central Asia	Integrated hydrologic-agronomic-economic model; model components used to evaluate effects of existing vs. optimized water policies, including mitigation of environmental issues and salinity caused by irrigation.	<u>Applied:</u> Complex model to represent physical river basin, GW in root zone, crop production, and profits from agricultural production. River basin network modeled as nonlinear program solved with domain decomposition. Two policy scenarios: 1) baseline in accordance with known institutions; 2) optimization resulting from subset solutions.	Agriculture	Optimized modeling results indicate total benefit increase of \$900 million over current policies, average crop yield increases, water withdrawal decreases, flow increases to Aral Sea, and a drop in salt discharge. Results support use of reservoirs as SW control to improve efficiencies in crop production and water conservation.
Goesch & Hafi, 2006	Dumaresq River valley, New South Wales and Queensland, Australia	Evaluate policy options to address GW externalities in situations of SW-GW interactions.	<u>Applied:</u> Uses simplified economic analysis of “double allocation” water supplies, where GW pumping reduces available SW under 2 scenarios, one of current water allocations and usage, and the other of increased GW pumping by upstream irrigators.	Agriculture	Results indicate inefficient allocations of connected SW-GW and regional economic losses of Australian \$0.5 million per year, if upstream irrigators utilize full pumping allocations. Where connectivity is well understood, policy options may include allocation of property rights to “shared” water and trading of rights.
Knapp & Olson, 1995	Kern County, CA	Develop decision rules for optimal GW withdrawals as a function of stock and SW flows.	<u>Theoretical - empirical:</u> Use economic model to evaluate optimal GW use under stochastic SW conditions, including artificial recharge. Key is tying GW levels to future pumping costs.	Agriculture	Aquifers serve as economic buffer to stochastic SW. Optimal decision rules found in conditions of increasing hydraulic head and decreasing SW flows. As noted in other studies, benefits from central GW management are small.

Table 3.1 continued

Noel et al., 1980	Yolo County, CA	Use optimal control model to evaluate policy options for allocation of SW and GW among agricultural and urban users.	<u>Theoretical - empirical:</u> Propose use of linear quadratic program to incorporate economic and hydrologic components so as to assess interaction between SW-GW system and water demands, and direct user costs. Location noted for conjunctive use operations with a lack of centralized planning.	Agriculture and urban	Model results indicate that size of GW resource and interdependence be carefully reviewed. Different hydrogeologic units may respond differently to pumping and therefore have different costs. Economic efficiencies may be experienced under tax vs. pro-rata allocations; both will increase the GW social value, but if GW overdraft is taking place, taxation provides greatest social value.
Provencher & Burt, 1993	Western U.S.	Evaluate effect of risk externality on management of GW as a common property.	<u>Theoretical:</u> Effects of stock, pumping costs, and risk externalities on GW pumping are modeled. Rate of pumping is assessed dynamically with feedback from central vs. private GW management strategies.	Agriculture	GW under decentralized or private management mitigates externalities of risk-averse decisions and common stock GW and may reduce associated costs.
Pulido-Velazquez et al., 2004	Southern CA	Apply a deterministic economic-engineering model and optimization rules to analyze flows, storage, and economic benefits in southern California's tiered water system.	<u>Applied:</u> Uses CALVIN (network flow economic-engineering model) and data from 11 water agencies in conjunctive use scenarios to assess flexibility and efficiency and to estimate value of conjunctive use programs.	Agriculture and urban	Flexible water markets plus improved conjunctive use efficiencies can reduce water scarcity and associated costs. The conjunctive use programs can generate marked regional benefits expressed in \$ million, including reduced SW imports.

Table 3.1 continued

Schuck & Green, 2003	Kern County, CA	Model the extent to which SW price may affect decision of farms to add GW well.	<p><u>Theoretical - empirical:</u> Evaluate the level of SW prices at which single farm irrigators are likely to adopt a well. Takes into account expectations of SW supply and water use decisions at margin</p>	Agriculture	SW may be replaced with GW when SW prices rise. The chances of well installations vary with land and aquifer characteristics.
Schuck & Green, 2002	Kern County, CA	Evaluate effects of supply-based water pricing on conjunctive water use with stochastic SW and changes in GW use.	<p><u>Theoretical - empirical:</u> Assess whether a supply-based pricing policy that includes grower profits, energy prices for GW pumping, SW costs (import water, deliveries, GW recharge) will enable water conservation.</p>	Agriculture (irrigation district)	In a supply-based system such as those with volumetric pricing, conjunctive use can mitigate SW price variations and GW over-exploitation. Optimal water prices encourage shift in crop production from low water periods to non-drought periods. Recommendation is to adopt tier-price system so as to simplify policy.
Tsur & Graham-Tomasi, 1991	Negev region, Israel	Model the value of GW as a buffer to uncertain water supply; measure change in GW value under dynamic vs. stable SW conditions.	<p><u>Theoretical - empirical:</u> Economic theory applied to conjunctive use problem - does GW serve as a buffer function?</p>	Agriculture	Solutions to proposed economic theorems prove that GW can serve as economic buffer for stochastic SW supplies.

Table 3.2 Common Parameters in Economic-Conjunctive Use Models

Category	Surface Water		Groundwater		Agriculture	Other
	Gains	Losses	Gains	Losses		
Physical Characteristics	Flow volume	Diversions	Volume available (stock)	Required discharge	Area of irrigated lands	Time period
	Upstream flows	System outflows	Natural recharge		Evapotranspiration	Water demands by use
	Return flows	Evaporation	Aquifer area			Area of study
		Infiltration	Hydraulic head			
		Deep percolation	Specific yield			
			Storage coefficient			
		Artificial recharge				
Economic Parameters	Revenues or benefits of use	Marginal cost	Revenues or benefits of use	Marginal cost	Crop-specific production costs	Present discount rate
		Withdrawals		Pumping costs per depth (pump lift)	Crop-specific revenue	
		Conveyance cost		Energy costs for withdrawal		
		Drainage collection		Artificial recharge cost, where applicable		

Table 3.3 Unique Economic-Conjunctive Use Parameters

Reference	Model Approach	Explicit Assumptions	Parameters Unique to Model
Acharya & Barbier, 2000	<p><u>General welfare estimation model</u>: Production cost \int [costs (seed, labor, etc.) + cost (GW pumping at different levels)]. Social welfare valuation \int (optimal conditions where marginal value of product = its price)</p>	<p>- Farmers produce a certain number and amount of crops under same price conditions. - GW available to a farm is dependent on GW level.</p>	<ul style="list-style-type: none"> • GW levels as valuation of social welfare (reduce uncertainty of seasonal rains)
Booker et al., 2005	<p><u>Hydrologic model</u>: Mass balance of SW inputs, outputs. Available GW accounted by “lagged functions of past river flows” <u>Economic valuation</u>: Separated by state and water use. Agriculture supply in CO accounted for through available GW and total annual Rio Grande flows; crop production dependent on SW priority rights. NM and TX valued by incorporation of price/yield by crop, into benefit function. Recreation value based on reservoirs along Rio Grande as function of volume. Municipal and industrial, per city, measured by integrating marginal benefits</p>	<p>- Costs of future GW flows beyond 6-year model period not included.</p>	<ul style="list-style-type: none"> • Economic valuation by sector (agriculture, municipal, industry, recreation) • Incorporation of legal (“law of the river”) and environmental constraints through SW flow calculations

Table 3.3 continued

<p>Bredehoeft & Young, 1988</p>	<p><u>Hydrologic simulation</u>: Linear program allocates stochastic SW flows to water users based on water rights \int (SW + return flows - reduced SW due to upstream pumping). <u>Economic valuation</u>: Individual farmers choose crops and acreage based on how much water is believed to be available, through SW rights and GW pumping, for the coming season. Uses semilog relationship between annual net benefit of pumping capacity and average stream flow</p>	<ul style="list-style-type: none"> - Stream diversions assumed to be 1 ditch company at upstream limit per sub-area - All water demands are for irrigation - Income estimated on prices, crop yields, yield adjustment coefficients, annualized capital cost of wells, operating costs. - To assess well installation benefit, relationship between low seasonal flow and net benefits apply across the system; net benefit at 1 location associated median critical flow is good estimate for system; acreage planted at median critical flow is good estimate for system 	<ul style="list-style-type: none"> • Well capacity as estimate of risk aversion in decisions to rely on SW, GW, or both
<p>Cai et al., 2003</p>	<p><u>Deterministic optimization model</u>: Integrates hydrology, agronomics, and economics in river basin network. Components: SW flow, salt transport, irrigation, drainage, crop production, benefit functions of water use and incentives; institutional controls. <u>Physical processes</u>: Water balance \int (SW flows, reservoir storage, drainage, percolation, evaporation); GW \int [inflow (recharge, percolation) – outflow (pumping, root zone extraction)]. Salinity summed at nodes \int (flow, concentration, storage). <u>Agricultural production</u>: Crop production \int (water, salt uptake, ET, growth stages) <u>Economic model</u>: Objective function to model irrigation profits at individual demand sites; central water allocation and incentives; benefits from hydropower, ecosystems.</p>	<ul style="list-style-type: none"> - Demand sites have individual benefits/costs, but model allocates water through central authority - Incentives (tax salt discharge and infrastructure improvement subsidies) indicate effectiveness of salinity control and conservation policies - GW movement is represented as a single tank at each node - All crop growth stages have constant efficiencies - No irrigation surface runoff 	<ul style="list-style-type: none"> • Use of SW flow variations to incorporate hydropower, ecologic benefits • Annual investments in infrastructure

Table 3.3 continued			
Goesch & Hafi, 2006	<p><u>Applied:</u> Basic economics of supply (Q_{SW} and Q_{GW}) and demand (Aus\$ / megaliter of water used) on connected SW-GW systems. Marginal net returns (revenue earned per megaliter water – direct costs of crop production for each additional megaliter of water). Base scenario – upstream irrigators pump GW and use SW; alternative scenario – upstream uses full GW and SW allocation, downstream users' SW is depleted by GW pumping</p>	<ul style="list-style-type: none"> - GW flows into river systems - GW pumping imposes costs on SW users only via reduced SW availability when a target is exceeded - No irrigation return flows - No environmental or other cost impacts - Assume 1:1 impact of GW pumping on reduced SW flows 	<ul style="list-style-type: none"> • Scarcity value of SW connected to upstream GW pumping
Knapp & Olson, 1995	<p><u>Hydrologic model:</u> $GW \updownarrow$ (changes in stock, percolation, recharge). SW varies over time with percolation losses. <u>Decision rules:</u> Optimal water management based on value function; tested using lattice program.</p>	<ul style="list-style-type: none"> - GW pumping is less than available stock - Recharge cannot be greater than available SW flows and is constant over time - Annual net benefit is bounded 	<ul style="list-style-type: none"> • GW valuation as a buffer to stochastic SW supplies
Noel et al., 1980	<p><u>Economic model:</u> Use of derived agriculture demands through linear program, stock opportunity costs, marginal pumping costs, and urban demand through indirect estimation. <u>Hydrologic model:</u> Use of changes in SW reservoir levels (from separate SW model) and groundwater levels (from finite element model) as indicator of GW changes in pumping, recharge.</p>	<ul style="list-style-type: none"> - Coefficients of GW stock variables in economic model allow determination of the effects of subsurface flow - In accordance with welfare function equation, economic value of flow is represented by producer surplus, or economic rent of agriculture, plus consumer surplus, associated with urban demand functions 	<ul style="list-style-type: none"> • GW valuation by hydrogeologic subunit is key to stock valuations, viable policy alternatives

Table 3.3 continued			
<p>Provencher & Burt, 1993</p>	<p><u>Hydroeconomic system:</u> User's GW net benefit \uparrow (net benefit from water use – GW pumping costs)</p> <p><u>Economic theorem:</u> Markov-Nash equilibria decision rules dealing with strategies of GW use, present and future, and GW use under conditions of stochastic SW supply. Incorporate individual vs. social/central management opportunity costs</p>	<ul style="list-style-type: none"> - Access to GW is limited by ownership of overlying land - GW consumed by a user in one period = GW pumped - GW pumped does not affect future SW availability - No irrigation returns to GW - Benefits of water use are greater than SW or GW consumption - SW is divided equally - Users consume GW only after SW is 100% utilized 	<ul style="list-style-type: none"> • Costs of GW use by individual firms vs. costs of GW use under central agency
<p>Pulido-Velazquez et al., 2004</p>	<p><u>Model:</u> Large scale “economic-engineering network flow optimization model,” CALVIN, used under 3 scenarios to evaluate efficiency of conjunctive use operations and resulting economic benefits.</p>	<ul style="list-style-type: none"> - Large data sets from 11 water agencies used for hydrologic inputs - Operational benefits include hydropower - Urban water use based on demand curves, separated into residential, industrial, and commercial - Agricultural demand data from statewide model - Model optimizes with “perfect knowledge of future flows”, not realistic for integrated water use - Real-time institutional operations fit into model constraints - Fixed GW pumping costs rather than variable as found in real time 	<ul style="list-style-type: none"> • Operational benefits and costs • Marginal willingness to pay by user, in this case, the water agency • GW storage value

Table 3.3 continued			
Schuck & Green, 2003	<p><u>Model basis:</u> Farmer will adopt a well when expected profits with a well are greater than expected profits without a well.</p> <p>Crop production ↓ (applied SW, GW, acreage, irrigation efficiency, land characteristics)</p> <p>GW pumping ↓ (energy cost, GW characteristics)</p>	<p>- Well installed when SW price is greater than marginal cost of GW, or threat of interrupted SW supplies is probable</p> <p>- Well adoption decision weighed through variables (soil permeability, field slope, crop acreage, pump lifts, irrigation efficiency)</p>	<ul style="list-style-type: none"> • SW price as control on water use • GW as stabilizing substitute for SW
Schuck & Green, 2002	<p><u>Supply-based water price-space model:</u></p> <p>Combine into social planners' model (dynamic Lagrangian algorithm) the aggregate grower profit ↓ (acreage, crop prices, SW price, energy price, GW level), changes in GW levels, district profit ↓ (volume of imported SW, ID financial reserves, and interest rate, or the rate of return on financial reserves)</p>	<p>- Growers respond to water prices in a manner that optimizes their resources</p> <p>- GW pumping and recharge occur in different time intervals</p> <p>- Financial reserves to stabilize costs in irrigation district from one period to the next</p> <p>- District's marginal costs, equivalent to SW price, are conditional upon imported SW volume</p>	<ul style="list-style-type: none"> • Water scarcity as measured by values in changes in aquifer storage • Financial reserves to stabilize costs in irrigation district from one period to the next
Tsur & Graham-Tomasi, 1991	<p><u>Model components:</u></p> <p>- Water revenue ↓ (price, agricultural inputs, water demand, use)</p> <p>- GW over time ↓ (recharge of stock – withdrawals)</p> <p>- Decision rules: 3 scenarios based on GW pumping decision made before or after SW supplies are known or are stable; optimal GW pumping plans using dynamic programming. Solve GW-SW profile for optimal withdrawals to steady-state.</p>	<p>To generalize the problem:</p> <p>- Water revenue increases</p> <p>- Supply of SW has no cost</p> <p>- Shadow price of GW is equivalent to opportunity cost of current GW pumping</p> <p>- Aquifer recharge is independent of SW received</p> <p>- Unit cost of GW pumping at any one level in the aquifer does not increase</p> <p>- SW supply is separate from GW pumping decisions</p>	<ul style="list-style-type: none"> • Shadow price of GW is equivalent to opportunity cost of current GW pumping • Calculated buffer value of GW

CHAPTER 4

THE IMPACT OF LEGAL SYSTEMS ON CONJUNCTIVE USE IN FIVE WESTERN U.S. STATES

Introduction

Conjunctive use, a water management strategy that optimizes surface and groundwater supplies, has been recognized and applied in certain locations since the 1950's.¹ Also known as conjunctive management, it is a fairly straightforward concept, technically feasible, and with a record of long-term programs applied in semiarid regions.² Many publications have documented significant findings in theoretical economics and applied conjunctive use studies, as well as efficient resource use through optimization. Taking advantage of basic surface and groundwater characteristics, it is considered particularly appropriate for application in semiarid regions subject to drought. Given these considerations, conjunctive use is surprisingly less known and utilized in some regions and states than might otherwise be anticipated. This research evaluates the effects, positive and negative, of different legal frameworks within five selected U.S.

¹ Other than informal employment of surface water and on-farm wells or springs as available, an early technical presentation on conjunctive use discussed the economic potential of in-ground storage options; see Harvey O. Banks, *Utilization of Underground Storage Reservoirs*, 118 TRANSACTIONS AM. SOC'Y. CIV. ENGINEERS 220-234 (1953).

² In the U.S., conjunctive use was initiated through proponents in Californian research institutions and water agencies; unsurprisingly, examples of long-term programs are found in Kern Valley and Santa Clara, beginning in the 1950's and continuing to this day; see generally Jack J. Coe, *Conjunctive Use – Advantages, Constraints, and Examples*, 116 (3) J. OF IRRIGATION & DRAINAGE ENGINEERING, 434-436 and 439-441 (1990).

states in which conjunctive use is either widely recognized or rarely used, providing a comparative basis for evaluating the supporting water laws.³

Western water law has contributed to the growth, development, and economic status of its states. Without sources of dependable, quantifiable, and reliable water sources, humans would not have been able to develop agriculture, municipalities, industry, and the associated economies, to the scale known today. Also critical to note are scarce water resources that require a legal system for recognized use and distribution. Due to the seasonal scarcity of water resources in the western United States, water law developed doctrines of appropriation and beneficial use. However, divergences between surface and groundwater laws have had definitive impacts on water management, both past and present.

Conjunctive use allows use of diverse sources during decreased water supplies and is managed differently in western U.S. states. Five states are selected as examples of similarities and differences in legal systems and correspondingly different approaches to conjunctive use. The various water laws in the states either support or deter conjunctive use, and much can be learned for future conjunctive use programs by evaluating existing state water laws.

An evaluation of conjunctive use studies in the literature indicates four major factors important for its successful application, these factors being the legal framework, the technical attributes of the physical surface water and groundwater systems within a

³ States in this research are selected due to changes in statutory and case law that allowed the growth and emplacement of conjunctive use programs. Founded on an involved legal system for surface and groundwater, California has long-standing programs. Colorado's legal system specifies conjunctive use of groundwater within the surface water rules. Due to a years-long drought in the Snake River Plain, Idaho has had recent legal battles concerning conjunctive administration rules vs. appropriative water rights. Washington has a statewide conjunctive administration system. Texas has several conjunctive use programs; however, the strategy is not widely applied in the state as compared to the other states under discussion.

region, the economics, and societal/stakeholder concerns and input. To place this review of state water laws in a similar perspective for discussing conjunctive use, this paper first provides a background of conjunctive use, water system components, and a summary of key economic factors. The overview is followed by a discussion of the role that water law plays in conjunctive use programs in the western United States. Development and changes over time in the water laws of California, Colorado, Idaho, Texas, and Washington indicate the manner in which conjunctive use programs have progressed under distinct legal systems. The interactions between conjunctive use programs and the legal systems of the state in which the strategy is in place, are then evaluated in light of legal issues and subsequent actions taken by specific programs. Lastly, the legal framework as a support or obstacle to future conjunctive use is considered for regions or water districts where the strategy has been seldom implemented.

Defining Conjunctive Use

Conjunctive use has developed over the decades in response to water demands, a need for different approaches to water management to best fit the basin, and research into the economics and technical capabilities of the strategy. The strategy initially focused on the economic advantages inherent in groundwater storage.⁴ Interest and research in the strategy grew based on the positive outcomes and proof of economic efficiency in theory. For example, new designs in algorithmic programming techniques assessed the design and operations for joint operation of a surface reservoir and aquifer in agricultural applications, research which also supported the exploration of economic viability of

⁴ See Banks, *supra* note 1.

conjunctive management approaches.⁵ Groundwater valuations were based on stochastic⁶ modeling of an “optimal inventory policy for ground water,” with the results firmly identifying conjunctive use as a viable water management strategy.⁷ Prior to the advent of powerful computational tools, conjunctive use was also analyzed in terms of systems and levels of associated issues⁸ and optimization of operations and controls for agricultural and urban water uses.⁹

Studies of conjunctive use continued to focus for several decades on economic analysis and agricultural efficiency. Optimal groundwater use with variable water supplies was evaluated utilizing user decision rules.¹⁰ A similar evaluation included artificial recharge as an economic consideration to assess the empirical aspects of a conjunctive use model.¹¹ With improvements in computer software design and power as well as increased user access, conjunctive use research incorporated large data sets in numerical models for basin-scale water availability and resource management decisions, thereby enabling more efficient decisions on water supplies for urban and agricultural uses.

The characteristics of conjunctive use are varied and changing. Discussions with water resource professionals concerning conjunctive use typically include the phrase, “It

⁵ Nathan Buras, *Conjunctive Operation of Dams and Aquifers*, 89:HY6 J. AM. SOC’Y CIV. ENGINEERS, 111-131 (1963).

⁶ Stochastic modeling refers to the state of expected changes in the model due to known changes in natural conditions.

⁷ Oscar R. Burt, *The Economics of Conjunctive Use of Ground and Surface Water*, 36:2 HILGARDIA, 31-97 (1964).

⁸ Reza Maknoon & Stephen J. Burges, *Conjunctive Use of Ground and Surface Water*, 70:8 J. AM. WATER WORKS ASSOC., 419-424 (1978).

⁹ Jay E. Noel, B. Delworth Gardner, & Charles V. Moore, *Optimal Regional Conjunctive Water Management*, 62:3 AM. AGRIC. ECON. ASSOC., 489-498 (1980).

¹⁰ Yacov Tsur & Theodore Graham-Tomasi, *The Buffer Value of Groundwater with Stochastic Surface Water Supplies*, 21 J. ENVIRON. ECON. MGMT., 201-224 (1991).

¹¹ Keith C. Knapp & Lars J. Olson, *The Economics of Conjunctive Groundwater Management with Stochastic Surface Supplies*, 28 J. ENVIRON. ECON. MGMT., 340-356 (1995).

depends ...,”¹² indicating a set of wide variations and expectations for the strategy. Almost every publication on the topic provides a definition of conjunctive use that aligns with the research study’s goal. Some definitions are similar, particularly within one discipline such as hydrology or economics.¹³ While a flexible approach to applying conjunctive use strategy is important to its successful implementation, variations in understanding, technical approaches, and goals can add to general confusion about its applicability. For this research, a slightly broad definition of conjunctive use is utilized, as follows: “In basins approaching full development of water resources, optimal beneficial use can be obtained by conjunctive use, which involves the coordinated and planned operation of both surface water and groundwater resources to meet water requirements in a manner whereby water is conserved.”¹⁴ Optimization of water supplies may be achieved through a variety of technical applications to realize goals such as water supply distribution, storage, and/or economic targets. Overall, successful conjunctive use adapts its approach under different physical, legal, and economic conditions. This research targets the legal frameworks under which conjunctive use may be effective.

¹² As part of the authors’ research into conjunctive use, interviews were conducted with water resource professionals from water law, economics, hydrology, groundwater, industry, modeling, and water agencies. This phrase is derived from the interviews.

¹³ Definitions from two economic publications demonstrate this point. E.g., Keith C. Knapp & Lars J. Olson, *The Economics of Conjunctive Groundwater Management with Stochastic Surface Supplies*, 28 J. ENVTL. ECON. & MGMT. 340 (1995) (“Since surface waters can be highly variable from one year to the next, aquifers also function as a natural inventory system for smoothing annual fluctuations in surface flows.”); Eric Schuck & Gareth P. Green, *Conserving One Water Source at the Expense of Another: The Role of Surface Water Price in Adoption of Wells in a Conjunctive Use System*, 19:1 WATER RESOURCES DEV., 55 (2003), (“... [C]onjunctive use refers to the practice of coordinating the use of surface water and groundwater resources during periods of water scarcity and surplus.”).

¹⁴ DAVID K. TODD & LARRY W. MAYS, *GROUNDWATER HYDROLOGY* 473 (3d ed., John Wiley & Sons, 2005). Dr. Todd’s view of conjunctive use changed over the years; in the book’s first edition of 1959, the text noted, “Maximum water development can only be attained by conjunctive utilization of surface and ground water reservoirs. Essentially, this requires that surface reservoirs impound stream flow which is then transferred at an optimum rate to ground water storage” (214). The change from a technical view to one that encompasses beneficial use of resources, coordination between agencies, and water conservation, also demonstrates changes in conjunctive use strategies.

Surface Water and Groundwater Systems

Conjunctive use strategy takes advantage of major characteristics in the hydrologic cycle.¹⁵ Surface water and groundwater can move at greatly different rates, and their storage is dissimilar in nature. Surface waters in streams and rivers tend to move quickly and can be measured in seconds and minutes. Replenishment of the surface water systems is a function of rainfall events, similarly measured, and may occur in many locations within a river's watershed over time. To develop means of transporting water, civilizations have found that surface water sources are more readily accessible for use and diversion. Infrastructure for surface water storage and use reflects this base of knowledge in the building of extensive dams, reservoirs, canals, and pipelines. Groundwater storage and flow, however, is dependent on the geologic matrix through which it moves. Flow rates can vary from minutes to years to tens of years. Aquifers are recharged through precipitation, percolation, and downward migration of water. Storage of groundwater occurs at various depths of the aquifer over time, reflecting differences in surface and subsurface geologies.

Where surface water and groundwater are both available, conjunctive management utilizes the advantages of their different characteristics such as seasonal surface water variability and naturally stored groundwater. Surface water is often the primary water source, being cheaper and more accessible than groundwater because of its proximity to water users, in-place infrastructure, and relevant legal framework developed over the years. Water users can include irrigated agriculture, municipalities, rural

¹⁵ Considered a closed system, water moves above and below ground towards low points, eventually reaching the ocean. Along this flow path, water evaporates or is transpired by vegetation into the atmosphere. The evaporated moisture eventually precipitates over the oceans and land, moving water from the vapor to the liquid phase. The hydrologic cycle is well described in many hydrology and hydrogeology texts; see Todd & Mays, *supra* note 14, at 13-27, for more detailed information.

constituents, and industry. If groundwater supplies are available within effective pumping depth and distance from wells to distribution systems, water districts may then opt to use pumped groundwater in times of low surface water flows and low rainfall.

Just as important as efficient water use is the interaction between surface water bodies and groundwater. In past water management planning, these interactions were at times considered negligible, particularly in regions not subject to frequent droughts or limited water supplies. Models have ignored these connections in order to simplify model algorithms, or because observations of water levels did not indicate the interactions in times of high flows and sufficient water availability. With the advent of measurable decreased flow of surface water resulting from groundwater pumping, interactions have become more important in defining water rights and modeling water availability scenarios.¹⁶ By treating the two systems as separate in time and space, yet connected by flow interactions, conjunctive use management can include quantifiable interactions in water balance and availability modeling.

Key Economic Factors

As noted above, water management strategies must be effective in their geographic locations; if a conjunctive use program is intended to rely on high quality groundwater as a supplement to a surface water source, then the program must be implemented utilizing an aquifer from which water may be effectively withdrawn and legally used. Should a surface water supply have reliable flows, then conjunctive use of groundwater may not be effective for the regional water demands.

¹⁶ U.S. Geologic Survey Circular 1139, *Ground Water and Surface Water, A Single Resource* (4th printing, 2006) (an overview of surface and groundwater interactions).

Just as important to conjunctive water use is its economic efficiency. As discussed above, economics research has been critical in establishing a theoretical basis for effective conjunctive use. Coupled to the physical characteristics of surface water bodies and aquifers that comprise a conjunctive use program, economic factors reflect these physical water systems. For a given conjunctive water use application, major physical characteristics include surface water inflows, historic flow rates, reservoir characteristics and releases, aquifer recharge and discharges, pumping rates across the aquifer, and data on the aquifer's yield. These characteristics are necessary components for the economic assessment. For example, revenue from benefits of the use of surface water and/or groundwater depend on the available water inflows, required upstream and downstream diversions, and the costs of operating and maintaining the water system infrastructure. In other words, the anticipated benefits of water use must account for associated costs before determination of possible economic efficiencies between water supplies, demands, and opportunity costs. Chapter 3 of this dissertation identifies common, or shared, economic parameters as well as unique parameters that are significant in planning a viable conjunctive use program. The groundwater-focused parameters are summarized as follows:

- Changes in groundwater levels as a measure of social welfare valuation, e.g., socio-economic conditions are improved through deliberate management of groundwater as measured by increases and decreases of water levels in the aquifer
- Groundwater valuation as usage cost for individuals versus a central agency
- Groundwater valuation as buffer, or a long-term storage stock, to variations in surface water supplies

- Groundwater sub-unit valuations as input to water management policy options
- Changes in groundwater storage used to estimate supply-based, surface water scarcity values
- Well capacity versus income and its variance can approximate risk aversion to unexpected changes in surface water flows.

The surface water-focused parameters are:

- Variable surface water flows to incorporate externalities - water laws, institutional allocations, hydropower, recreation
- For interconnected surface water and groundwater systems, value surface water scarcity through effects of upstream groundwater pumping
- Water users' marginal willingness to pay
- Surface water price as control on volume of water use

Lastly, the water system-focused parameters are:

- Water use valuations by sector (agriculture, urban, hydropower, recreation)
- Operational costs and benefits.

These parameters underscore the flexibility of conjunctive use as a water management strategy and groundwater use as a stabilizing factor in variable surface water supplies, as well as the effect of non-economic factors outside economics. They also emphasize a fundamental benefit of conjunctive use – namely, the applicability of conjunctive strategies to diverse regions and water management issues.

Legal Foundations for Conjunctive Water Use

Water management strategies require a legal framework within which the technical approach can be developed to ensure a water supply and address other water

management goals. Without the legal right to divert, store, and retrieve water, degrees of uncertainty and risk influence potential water transactions. Water management via conjunctive use is no exception.

In general, western states established water laws over the last 150 years based on English and American common law and laws from Spain and Mexico. Western water law evolved in a geography dominated by few rivers and large expanses of semi-arid and arid lands. The riparian, river-bank dominated laws of the eastern United States were not well-suited for the west. Rather, “first in time, first in right” made sense to the settlers and water uses of western states, the phrase indicating a system in which the first landowners to pay for and manage permits were among the first to receive water allocations. Thus, prior appropriation, the term by which the system was known, became the primary approach to legal divisions and allocations of water.

Conjunctive use, although practiced in some eastern states, is more suited to the water-stressed west. With regard to conjunctive use, no one law is necessary for such a water strategy to be implemented. What laws and legal strictures allow conjunctive use to function as a viable water strategy? While the physical systems and economics of conjunctive use have received much research and attention, the laws that support conjunctive use should also provide insights to its future viability.¹⁷ Therefore, this research reviews water laws in states that actively support some form of conjunctive use, thereby providing a basis for comparison between states where conjunctive use is fairly well established and where it is less often found.

¹⁷ Other research has focused on different aspects of western water law or its implications on integrated water; see generally Edella Schlager, *Challenges of Governing Groundwater in U.S. Western States*, 14 *HYDROGEOLOGY J.* 350-360 (2006); Barbara Tellman, *Why Has Integrated Management Succeeded in Some States but not in Others?*, 106 *J. CONTEMP. WATER RESEARCH & EDUC.* 13-20 (1997) (formerly *Water Resources Update*).

In selecting states, the research focus is on interactions between water law and conjunctive use potential. The following sections summarize the primary water laws that may affect whether conjunctive use is a viable alternative for water management. The selection of states is not intended to represent all western states, water laws, and water management programs. Complete review of water laws in any one state, the institutions that carry out or enforce those water laws,¹⁸ and federal and Native American water laws, are beyond the scope of this analysis. For example, the California Water Code contains tens of thousands of statutes to regulate water rights, permits, agencies, allocations, flood control, diversions, etc. However, only the subsections that bear on conjunctive use are reviewed. Similarly, water laws and rights associated with federal reserved rights, Indian nations, and interstate compacts provide topics that are not the focus of this work and therefore are not covered by this research. However, the laws and statutes concerning support of conjunctive use development offer insights towards analysis of conjunctive use programs that have evolved in different states, and what legal framework(s) may support conjunctive use in the future.

Four western states, California, Colorado, Idaho, and Washington, have formed distinct water law systems and conjunctive use programs and thus providing a solid foundation for this review. California's conjunctive use programs have changed and grown over the decades. Early programs of the 1950's typically focused on agricultural water management alternatives under state-led oversight of the programs. Currently, programs are more likely to observe conjunctive partnerships between a state assistance

¹⁸ WILLIAM A. BLOMQUIST, EDELLA SCHLAGER, & TANYA HEIKKILA, *COMMON WATERS, DIVERGING STREAMS: LINKING INSTITUTIONS AND WATER MANAGEMENT IN ARIZONA, CALIFORNIA, AND COLORADO* (Resources for the Future Press, Washington D.C.) (2004) (an excellent review of conjunctive use and associated institutions in three western U.S. states).

program and a local groundwater basin. In addition to agriculture water demands, the partnership often includes urban concerns. A different conjunctive approach is found in Colorado. Due to groundwater withdrawals that affect surface water flows and lawsuits from downstream states, in the 1960's Colorado moved towards conjunctive use through the legal system. Groundwater permits were incorporated into Colorado's legal system for surface water, thus attempting to ensure that senior surface water rights would not be affected by groundwater users. The result is an integrated legal system and conjunctive use programs that concentrate on surface water augmentation rather than optimization of water sources. In 1994, Idaho established rules for co-administration of surface and groundwater permits. Drought in the Snake River Plain, a region of agriculture, hydropower generation, and rural water users, caused legal challenges and increased awareness of the interconnections between surface and groundwater.

Washington has conjunctive administration of surface water and groundwater, resulting in de facto conjunctive water management through a permitting process that considers the effects on other sources of diverting one water source on other sources. In comparison to these four states, Texas has appropriative water rights for surface water, and groundwater is primarily a property owner's right to capture as amended by rules of locally controlled groundwater conservation districts. Texas is not a state known for its conjunctive use programs, though several are to be found.

Which legal systems and rules may encourage conjunctive use implementation, and which systems discourage its deployment? A comparison of the legal systems and conjunctive use programs provides insights to this question. The following sections give an overview of the principal legal approaches to water rights and allocations in the five

states. A summary of the states' legal approaches to surface water and groundwater doctrines and rules is located in Table 4.1.

California's Complex Water Law System

As with other western states, California's water laws evolved over time and were affected by legal battles and sustained droughts. In particular, water use in response to three stress factors – water availability, variability in sources, and positive growth rates in agriculture, population, and industry – played a strong role in how statutory and case law were applied.¹⁹ Differing geographies across the state are also important. In northern California, surface water is readily available and seasonally replenished in multiple streams and rivers. In central and southern California, however, rainfall is dispersed intermittently in semi-arid to arid climates, resulting in fewer major rivers. In addition to these climatic benefits and constraints, one of the largest and most productive agriculture regions in the United States became established as did urban centers of high growth rate. State water law in California changed over time to encompass the realities of sustaining the high agricultural yield and population growth under water-stressed conditions and competing water uses.

To meet the changing demographics and water needs over time, California authorized multiple approaches to water rights. The California Water Code provides that waters belong to the people of the state.²⁰ Under Article X, Section 2, of the California Constitution, diverted or appropriated waters must be put to reasonable and beneficial

¹⁹ Blomquist et al., *supra* note 17, at 3-5, stress how these factors have affected water issues and institutional actions in the states of Arizona, California, and Colorado.

²⁰ CAL. WATER CODE, Title 23, § 102 (this section also notes "... the right to the use of water may be acquired by appropriation in the manner provided by law"), at <http://www.leginfo.ca.gov/cgi-bin/calawquery?codesection=wat&codebody=&hits=20>.

use.²¹ Some of the earliest water rights were riparian, those being the rights of landowners having streams running through or adjacent to their property to the use of those waters.²² As with diverted or appropriated waters, riparian rights are subject to reasonable and beneficial use. As water uses for mining and agriculture increased in California, a priority system, also known as prior appropriation, was established. Application for prior appropriation water permits was initiated after 1914,²³ with the requirement that permitted waters must be put to beneficial use. The permitted use must show continual, beneficial use, or the user may lose the right to the water within five years. Surface water and groundwater rights, and the associated oversight by institutions, are recognized as separate systems in California.²⁴

In California water law, one special situation is known as pueblo water rights. These rights originated during Spanish colonization of land in present-day California cities and can hold precedence over younger (later) water rights.²⁵ Case law established pueblo rights for a few municipalities through court decisions. These rights are confined within boundaries of the current municipality and to addressing water needs within those boundaries. The pueblo water rights provide a small but legally backed water right to surface water and groundwater within the watershed.

²¹ See *id.* § 100 (with discussion on beneficial use and unreasonable use or waste of water).

²² See *id.* § 100 (with regard to the right to “natural flows”); § 101 (with regard to riparian rights and beneficial use of waters on lands with water running through or adjacent to those lands). A permit is not required for riparian rights, and the right is not transferable. However, there are limits established by case law; see generally State Water Resources Control Board, *Information Pertaining to Water Rights in California* (1990), at http://www.waterboards.ca.gov/waterrights/publications_forms/forms/docs/app_general_info.pdf.

²³ See State Water Resources Control Board, *supra* note 21, at 6-7.

²⁴ William Blomquist, Tanya Heikkila, & Edella Schlager, *Institutions and Conjunctive Water Management Among Three Western States*, NAT. RESOURCES J. 653, 666-673 (2001) (brief overview of California case law with regard to groundwater, its different classifications, and the impacts of state law upon conjunctive management programs in the state).

²⁵ *Id.*, n. 70.

Another facet to California water law is that of the Public Trust Doctrine. The now-famous case, in the perception of the environmentalist movement, of Mono Lake supporters who wished to see the lake returned to its former state versus the City of Los Angeles that had diverted Mono Lake tributaries for decades developed into a court decision that merged the existing water rights system and the public trust doctrine under specifications of reasonable use.²⁶

Statutes and cases involving groundwater in California came after surface water laws and establishment of rights, often placing groundwater in a legal status subordinate to that of surface water rights. California has two general classes of groundwater, those named “subterranean” waters, regulated under surface water rules, and “percolating” groundwater which is generally unregulated. Subterranean water is defined as “flowing through known and definite channels,” and use of such water is subject to appropriation permits under the surface water rights system.²⁷ Under the second classification, percolating groundwater is considered a common source that is subject to overlying land use and correlative rights. Correlative rights to groundwater are those shared by land owners whose properties overlie the aquifer.²⁸ The owners can pump non-quantified volumes of groundwater for beneficial use, limited only by the cumulative yield of the aquifer. The amount of percolating groundwater in the aquifer that has not been

²⁶ Leigh A. Jewell & Craig Anthony (Tony) Arnold, *The Real Public Trust Doctrine: The Aftermath of the Mono Lake Case*, in BEYOND LITIGATION: CASE STUDIES IN WATER RIGHTS DISPUTES (Craig Anthony Arnold & Leigh A. Jewell ed., Envir. L. Institute) (2002), 155-190. The court decision in *National Audubon Society v. Superior Court of Alpine County*, 33 Cal. 3d 419, 189 Cal. Rptr. 346 (1983), was a landmark insofar as the public trust doctrine was merged, rather than becoming dominant or subject to, the existing California water rights system.

²⁷ *Supra* note 19, § 1200.

²⁸ Nathan Eric Hampton, *Costs of California's Correlative Rights Doctrine as a Solution to Groundwater Overdraft*, VIII:4 CONTEMP.POL'Y ISSUES, 106, 107-108 (1990). As a base to its economic analysis, the article discusses correlative rights' doctrinal basis in California case law (*Katz v. Walkinshaw*, 1903). N. 1 provides further clarification of correlative rights through allocation of groundwater as a private property right in overdrafted basins (*City of Pasadena v. City of Alhambra et al.*, 33 C. 2d 908, 207 P. 2d 17 (1949)).

appropriated through correlative rights is considered “surplus” and may be appropriated for non-overlying land use. Rights to this water are junior to overlying land use and the associated correlative rights to groundwater.²⁹ Water users and suppliers that import permitted water into a river basin have the right to pump and utilize return flows, also known as irrigation runoff, of those same imports.³⁰ As previously noted, pueblo rights to surface water and groundwater may supersede other rights.³¹

Groundwater basins are recognized as critical to the state but subject to depletion or water quality impairment.³² Therefore, groundwater basins have been and continue to be adjudicated, legally allowing limits on groundwater pumping and water master control under court-ordered conditions.³³ Add these classifications and exemptions to multiple sets of rules, and the result is an imposing body of statutory and common law for California groundwater.

Colorado: Prior Appropriation and Tributary Groundwater

Colorado was one of the first western states to codify, or bring into legal status through legislative and statutory action, the system of prior appropriation. Western settlers realized there was a conflict between established riparian water laws suitable to the east and the fact that there were fewer rivers in the west along which water could be diverted and used by a majority of landowners. Mid-nineteenth-century mining operations also recognized that riparian rules were not suitable for mountainside claims, and that to realistically work such claims water would have to be diverted by non-

²⁹ See Blomquist et al., *supra* note 23, 667, n.68. “Surplus” groundwater may be used through pumping and conveyance to overlying and non-overlying lands.

³⁰ *Supra* note 23, 668.

³¹ *Supra* note 23.

³² *Supra* note 19, § 12922, 12922.1.

³³ National Water Research Institute, *Conjunctive Use Water Management Program Workshop Report*, (National Water Research Institute CD-ROM, Occasional Paper No. NWRI-98-02, Thousand Oaks, California), 17 (1998).

property owners. In 1876, Article XIV of the Colorado Constitution was adopted, clearing the way for the state's appropriation system.³⁴ The formal permit system under the prior appropriation doctrine was initiated along with requirements such as beneficial use of the appropriated waters. Colorado also created a system whereby permit applications not yet fully realized could still be submitted and assigned a priority date. These water rights are known as "conditional" rights and allow the applicant time to plan and build necessary structures such as diversions and canals to ensure beneficial use. Adjudicated permits are known as "absolute" water rights in the Colorado water law system. Under this system, water rights are considered property, and thus can be bought and sold, leased, and transferred.

Groundwater rights followed a different evolution. As installation of wells became cheaper with changes in technology, more wells were installed during the 1950's and 1960's, particularly near known water-producing areas and rivers.³⁵ Due to the geology of these areas, the rivers and aquifers are highly interconnected, e.g., large volumes of groundwater pumping are likely to cause reduced surface water flows. Water users with senior rights were concerned their water needs would not be met under reduced flow conditions. Colorado thus began management of groundwater under existing surface water rules with the 1965 Ground Water Management Act, which established that all groundwater is tributary, or connected, to surface water, unless proven

³⁴ COLO. CONST. art. XVI, §§ 5-6 (the 1876 Colorado Supreme Court also ruled for appropriation rather than riparian rules). §§ 5: "The water of every natural stream, not heretofore appropriated, within the state of Colorado, is hereby declared to be the property of the public, and the same is dedicated to the use of the people of the state, subject to appropriation as hereinafter provided." §§ 6: "The right to divert the unappropriated waters of any natural stream to beneficial uses shall never be denied. Priority of appropriation shall give the better right as between those using the water for the same purpose..."

³⁵ *Supra* note 23, at 673-680.

otherwise.³⁶ In other words, tributary groundwater is subject to prior appropriation rules under the Colorado water court system.

A systematic approach towards administration of groundwater, wells, and water rights was further defined in the 1969 Water Rights Determination and Administration Act. Specifically, well permits were required to establish a priority date. Considering the high number of well owners with permits by the date of the Act, out-of-priority or junior diversions were allowed through the concept of “augmentation” of surface water flows. Augmentation programs involved the purchase of surface water rights and leases to be held by the State Engineer’s office for release during low surface water flows. The Act also required that waters of the state be maximized for as many uses as possible, thus expanding definitions of beneficial use.

Hydraulic and Legal Interconnectivity in Idaho

As with many other western states, prior appropriation is the basis for water laws in Idaho.³⁷ However, prior appropriation is utilized in Idaho for both surface water and groundwater. Although all waters of the state are public waters, permits under the prior appropriation system ensure the right to beneficial use of diverted water.³⁸ The state’s geography can be generally divided between high plains and mountain ranges.

Variations in geography, geology, and water systems endow the state with valuable natural resources and varied water uses. These uses include irrigated agriculture, mining,

³⁶ The tests to prove that groundwater is “non-tributary” to any surface water body in Colorado is quite rigorous. The application must prove that the diverted groundwater will not deplete any surface stream more than 1/10 of 1 percent of the proposed groundwater diversion, annually, for up to 100 years. If a non-tributary aquifer is legally determined, then the water in the aquifer is allocated based upon percent of land owned above that aquifer.

³⁷ IDAHO CODE § 42-106 and § 42-107 (establish the basis premise of prior appropriation) at <http://www.legislature.idaho.gov/idstat/TOC/IDStatutesTOC.htm>.

³⁸ *Id.* at § 42-101, establishes certain water classifications as public waters; § 42-103 allows for appropriation of surface and ground, or “subterranean,” waters; § 42-104 establishes beneficial use.

lumbering, ranching, hydropower, geothermal use, and municipal development, and water conflicts exist between the uses.³⁹

Much of the early surface water use by western settlers in Idaho was devoted to agriculture, particularly in the Snake River Plain.⁴⁰ By far the greatest use for mid-nineteenth-century settlers, surface water appropriations for crops began around the 1870's through diversion points and canals. Prior to May 20, 1971, surface water rights were ascertained through establishing diversion point, appropriating water, and putting it to beneficial use. After the May 1971 date, surface water rights were established via filing applications with the state water agency responsible for surface water and groundwater allocations, the Idaho Department of Water Resources. The permit process, rights, transfers, and licenses for the permit system are covered in the Idaho water code.⁴¹ The only surface water use exempted from the permit process is that of "instream livestock" use, allowing landowners to water their herds and livestock without requiring a physical point of diversion.⁴²

Groundwater is part of the prior appropriation system. Prior to March 25, 1963, groundwater could be appropriated by pumping and putting the water to beneficial use. After this date, groundwater diversions must be permitted under the same application process as surface water. There are exemptions for domestic use with limits.⁴³ Idaho

³⁹ An overview of physical water and water rights in Idaho can be accessed through the National Water Rights Digest Reference, at <http://www.ridenbaugh.com/nwrd/nwref/id.htm>.

⁴⁰ Donna M. Cosgrove, Gary S. Johnson, & David R. Tuthill, *The Role of Uncertainty in the Use of Ground Water Models for Administration of Water Rights*, 140 J. CONTEMP. WATER RESEARCH & EDUC., 30, 32 (2008).

⁴¹ IDAHO CODE § 42 (chapters 2 through 5 establish permits, allocations, and procedures among water rights holders as required for surface water, groundwater, low-temperature geothermal waters, and waters transferred outside of the state).

⁴² *Id.*, §§ 42-113, 42-114 define livestock watering uses and rights.

⁴³ *Id.*, § 42-111 ("Domestic purpose" or "domestic use" is generally limited to water for single-family uses, including homes, camps, livestock, and irrigation of up to one-half acre of land, if total use does not exceed

also has statutes for geothermal groundwater of temperature exceeding 212 degrees F.⁴⁴ Of future interest is the state requirement for “full economic development of underground water resources,”⁴⁵ a concept that was called into question during later lawsuits concerning a major aquifer and its users in the Snake River Plain.

Years of droughts, floods, increasing water uses and demands, and limited water allocations have added stress to the legal framework. In particular, the high degree of interconnectivity between surface water and aquifers observable over time in the increases and decreases of spring flows, attributable to the impacts of greatly increased use of either surface water or groundwater, resulted in the creation of conjunctive administrative rules for surface water and groundwater.⁴⁶ As discussed later in the section concerning conjunctive use programs, the legal system in Idaho does not correspond well to the physical interactions of surface water and groundwater. The gap between the legal and physical water systems caused legal disputes about the primacy of water rights versus administrative rules.

Washington’s Merger: Statewide Conjunctive Administration

Water laws in Washington developed over time through statutory and common law responding to changes in water needs. What is less typical than in other western states is the joining of surface water and groundwater rules and administration, which occurred as early as 1945. The result is a statewide conjunctive administration of surface water and groundwater. Water rights are overseen and administered by the Department

13,000 gallons per day. The statute allows other uses if the total does not exceed 0.04 ft³/sec or diversion volume of 2,500 gallons per day).

⁴⁴ *Id.*, §47, chapter 16.

⁴⁵ *Id.*, § 42-226.

⁴⁶ *Id.*, § 42-237 (administration of this rule is codified under IDAHO ADMIN. CODE, Title 03, Chapter 11; at <http://adm.idaho.gov/adminrules/rules/idapa37/0311.pdf>).

of Ecology, an agency responsible for oversight of water supply and quality, dams and reservoirs, and other water matters.⁴⁷

Washington water laws began under the riparian doctrine in the mid-nineteenth century.⁴⁸ However, as with other western states, diverse geography, mountains with relatively high rainfall and numerous rivers, high plains with fewer major rivers but arable acreage, and growth of mining and timbering industries along with a growing population, all combined to require an approach to water rights more suited to the needs. Prior appropriation slowly became the new water rights system, first through usufructuary rights, or right of use by landowners or permit holders, as determined through court cases in western states,⁴⁹ followed by the growing awareness of citizens and their legislative bodies that prior appropriation, or the right to divert water and put it to beneficial use under reasonable conditions, was more suitable for the West. Moreover, the water right was not a right to ownership of water but rather a right to divert and use water.

Prior appropriation as a matter of water doctrine and statewide approaches to water management entered legal discussions and lawsuits in the late nineteenth century in Washington. Court cases in Washington increasingly determined the applicability and implementation of appropriated waters with priority dates to establish the timing of the right. In 1917, prior appropriation became codified under a fixed and durable system of

⁴⁷ Christine O. Gregoire, James K. Pharris, and P. Thomas McDonald, AN INTRODUCTION TO WASHINGTON WATER LAW, Washington Office of State Attorney General (January 2000), at <http://www.ecy.wa.gov/PROGRAMS/wr/rights/water-right-home.html>. (Washington Department of Ecology provides an extensive overview of water law development, including case law for surface water and groundwater).

⁴⁸ *Id.*, II-5 to II-11.

⁴⁹ *Id.*, I-2 to I-3.

surface water administration.⁵⁰ However, it took years of lawsuits and jurisprudence before the riparian and appropriation doctrines, and their associated water rights, were merged into a workable legal system for the state.⁵¹ In addition, three concepts help define prior appropriation under Washington water law – beneficial use, the appropriation date, and appurtenancy, or the legal connection between appropriated water and application to specific parcels of land.⁵²

Disputes over groundwater followed technical advances in well drilling; thus, the laws dealing with groundwater rights developed more slowly than those of surface water. For the first part of the twentieth century, rights pertaining to groundwater were argued in court rather than established through statutory law.⁵³ This situation changed with the enactment of a code for public groundwater that brought groundwater under the prior appropriation system. Considering the times and available scientific knowledge about the nature of aquifers, definitions in the code were surprisingly unclear on “underground” versus “percolating” groundwater.⁵⁴ Inclusion of the public groundwater of the state into the surface water permitting system, as well as natural and artificial recharged waters, allowed the state of Washington to begin the process of what would later be known as conjunctive administration. The basic system has remained intact to the present day, thus establishing a foundation of how surface water and groundwater are managed across the state.

⁵⁰ WASH. REV. CODE § 90.03 (the water code makes explicit the public nature of the waters of the state, the right of appropriation, determinations, and procedures). The revised codes are available at <http://apps.leg.wa.gov/RCW/default.aspx?cite=90.03>.

⁵¹ See *supra* note 46, II-18 to II-28.

⁵² See *supra* note 46, Summary 5 – 7.

⁵³ See *supra* note 46, V-4, V-7.

⁵⁴ See *supra* note 46, V-7 to V-8. Also, see WASH. REV. CODE § 90. 44.

Texas: Prior Appropriation and Rule of Capture

In this review of state legal systems as a basis for determining whether conjunctive use is implemented as a water management approach, Texas, a state with few conjunctive use programs, is discussed with regard to its prior appropriation system for surface waters and its unique approach to groundwater use and management. The review allows comparison and analysis of fundamental water laws between states, followed by evaluation of similarities and differences in conjunctive use development within these same states.

As previously noted, English law was utilized as a precedent for state water law in the United States in its early development stages, particularly in regard to western water law. In Texas, both Mexican law with Spanish origins and English laws were in place prior to the voluntary annexation of Texas into the Union as the 28th state in 1845.⁵⁵ Spanish and Mexican laws focused on grants of land but said little about water. In response to subsequent water disputes, the Republic of Texas adopted English common law, based on riparian rights, in 1840.⁵⁶ Due to geographic factors such as few rivers in West Texas, the need for legal rights to water on lands without a river, and continued disputes, Texas adopted the Irrigation Act of 1889, which adopted prior appropriation for the arid western portion of the state.⁵⁷

Prior appropriation worked so well in regard to the state's water needs that it was adopted within two decades for all lands within state boundaries. However, as

⁵⁵ TEX. CONST. art. I, § 1: "Texas is a free and independent State, subject only to the Constitution of the United States...".

⁵⁶ Ronald A. Kaiser, J.D., HANDBOOK OF TEXAS WATER LAW- PROBLEMS AND NEEDS, Texas Water Resources Institute (Texas Agriculture Experimental Station, Texas A&M University, College Station, Texas, 1987), 6.

⁵⁷ *Id.*

Washington and other states found, it was not without additional legal disputes over riparian versus appropriative rights. For example, a 1917 amendment to the Texas Constitution⁵⁸ included a requirement for adjudication of state waters as well as regulation prior to such adjudication. Four years later, that portion of the amendment was found to be unconstitutional. Not until 1967, a decade after the worst drought on record for Texas, was the necessity to ascertain legal claims and all water permits in the court system again established under the Water Rights Adjudication Act.⁵⁹ The Texas Water Code describes the rules and regulations for water rights, permitting, and, more recently, addresses concerns such as environmental flows.

In general, groundwater law in Texas can be summarized in the phrase “rule of capture,” based on English common law.⁶⁰ This rule, right of land ownership, is considered to include access and usage rights to subsurface water under the land. Due to the lack of information about groundwater flow, the English court that initially adopted the rule also held that “any inconvenience to his neighbor[’s well] falls within the description of *damnum absque injuria*.”⁶¹

Based on reasoning similar to English common law and subsequent court decisions made in other courts in the United States, the Texas Supreme Court adopted the rule of capture near the turn of the 20th century upon conclusion of the court case

⁵⁸ TEX. CONST., art. 16, § 59. The “conservation amendment” gave right to the State to conserve and develop natural resources, parks, and associated facilities. See also Kaiser, *supra* note 54.

⁵⁹ See *supra* note 54.

⁶⁰ The English case dates to 1843, founded on property rights, the need and capability to withdraw water from the ground, and limited understanding of groundwater flow (*Acton v. Blundell*, 12 Mees. & W. 324, 354, 152 Eng. Rep. 1223, 1235 (Ex. Ch. 1843)). The ruling of the court did not grant ownership of subsurface waters; rather, the decision was that well owners did not owe care to prevent damage to their neighbor’s wells.

⁶¹ *Id.* (In considering *Acton v. Blundell*, the English court reasoned that movement of water beneath the ground was unknowable, therefore, a landowner who put in a well could not be blamed for possible changes or disturbances in his neighbor’s well. Thus rule of capture falls into the category of *damnum absque injuria*, or injury without a remedy.).

*Houston & T.C. Ry. Co. v. East.*⁶² The case involved the drying of a landowner's shallow well after a deeper well dug for the Houston & Texas Central Railway produced greater quantities of water. Emphasis in the Texas Supreme Court's decision, which reversed a lower court decision, was the lack of liability for a landowner's actions on its land, and the flow of groundwater being inexplicable.⁶³ This ruling initiated the legal foundation of groundwater as tied to property rights through common law in Texas. This foundation, however, lacks the legal right to address limitations on water use and administration.

Also called "the law of the biggest pump," the rule of capture allows a landowner to pump all the water that can be extracted from under his/her overlying land, with certain exceptions. In the above-noted *East* case, the court also noted that pumped water must be beneficially used and not wasted.⁶⁴ Other constraints on groundwater use developed over time. Groundwater pumping may not be done as to maliciously or intentionally injure adjacent property.⁶⁵ Pumping in the Houston area caused significant land subsidence in the 1960's and 1970's, and subsequent lawsuits resulted in a court decision that found well owners can be liable for causing land subsidence.⁶⁶

Legislative actions with regard to groundwater were given authority through the 1917 Conservation Amendment, which authorized the state to regulate and conserve natural resources, including water. In 1949, the Texas Legislature enacted statutes for

⁶² *Houston & T.C. Ry. Co. v. East*, 81 S.W. 279, 281 (Tex. 1904).

⁶³ The Texas Supreme Court quoted from a ruling on a similar case of groundwater from the Supreme Court of Ohio (*Frazier v. Brown*, 12 Ohio St. 294). The quote deals with the "practical reasons" behind the Texas court decision, specifically that "... the existence, origin, movement, and course of such [ground]waters, and the causes which govern and direct their movements, are so secret, occult, and concealed that an attempt to administer any set of legal rules in respect to them would be involved in hopeless uncertainty ...".

⁶⁴ *East*, 81 S.W. at 282.

⁶⁵ *City of Corpus Christi v. Pleasanton*, 276 S.W.2d 798, 801.

⁶⁶ *Friendswood v. Smith-Southwest Indus.*, 576 W.W.2d 21 (Tex. 1978).

creation of underground water conservation districts.⁶⁷ In accordance with Texas Constitution Article 16, Section 59(b), the statute allows each district the authority for groundwater management as conferred by its enabling legislation. However, not all districts were created through legislation. As well, the districts have demonstrated different approaches to groundwater management and permitting. Over the years, almost 100 conservation districts have been created in Texas, each with rules that vary in regard to different degrees of authority and enforcement. The groundwater legal situation is made more complex with special districts, the Edwards Aquifer Authority of central Texas and subsidence districts in the Harris-Galveston and Fort Bend regions being good examples.

In the above discussion and review of basic water laws in selected western states, similarities are striking. Each state began with the riparian doctrine during its early days of settlement, but soon found prior appropriation and a systematic approach to surface water permits to be most suitable for resolving water disputes as well as supportive of varying economic and social development. Groundwater rights and permitting typically developed after surface water rules, resulting in groundwater rights often placed in a status secondary to those of surface water.

Classification of, and rules for, groundwater developed in a different manner for each state. California has several classifications of groundwater, one of which, “subterranean” or stream underflow, is considered a type of surface water and therefore subject to its permitting rules. Correlative rights of landowners overlying an aquifer are used to resolve “percolating” groundwater rights and disputes. Certain conditions apply

⁶⁷ TEX. WATER CODE §36; see also Kaiser, *supra* 54, 6. Of note is § 36.001(21), which defines conjunctive use to mean “... the combined use of groundwater and surface water sources that optimizes the beneficial characteristics of each source.”

to both surface and groundwater, such as pueblo rights dating back to the time of Spanish occupation of California and the public trust doctrine. Colorado established new water rights by being the first western state to eradicate the riparian doctrine, setting up water districts, each with its own water court and adjudication, and legislating the majority of aquifers into surface water permitting. Washington further simplified water laws by conjunctively managing surface water and groundwater; no permit is issued for diversion of either water source without consideration of its effects on the other source. Idaho's system of separate surface water and groundwater permits, and conjunctive administrative rules, has come under severe dispute in the last ten years as drought has magnified the degree to which water rights and available quantities are intertwined. The distinct system in Texas of appropriated and adjudicated surface water rights, and variability in pumping rules across groundwater conservation districts, may generate similar cause for concern during times of drought in Texas.

Conjunctive Use Goals vs. Legal Issues

Water management approaches are selected in the context of what is judged best for the region or society at the time of needing the management. Water management goals guide the selection of an approach by water managers and stakeholders. For example, creation of large reservoirs was a favorite approach of western states for several decades, particularly when federal aid and funding were offered to support the storage of surface waters that would help in flood control, support recreation, and allow controlled releases for interstate water supply. Conjunctive use was more likely to be selected when the strategy of coordinating and optimizing surface water and groundwater was well understood and the water management goals were targeted towards the need to make

better use of available supplies through existing surface water infrastructure in addition to groundwater storage and supply. As several authors pointed out, a primary advantage of conjunctive use is its inherent flexibility,⁶⁸ allowing changes in the overall program to meet changing needs of water demands, demographics, and climatic conditions.

A water management program typically has multiple goals, but depending on the circumstances, one or two goals are usually prominent. Goals are tied not only to desired outcomes of water management but also to benefits and costs. Blomquist and Sahuquillo note that coordinated use of surface water and groundwater allows a greater range of values in water use.⁶⁹ These potential benefits include reducing the effects of droughts and flooding, recharge of overdrafted aquifers, use of the storage capacity inherent in certain types of aquifers, augmentation of stream flows through stored groundwater or leased water, improvement of water quality such as diverting high quality groundwater into a stream undergoing salinity issues, environmental habitat support, and climate change.

Legal factors play no small role in viable water management. With regard to conjunctive use, several factors and legal impediments were identified in a 1998 workshop focused on conjunctive use in California.⁷⁰ Important components of legal impediments identified by the water management professionals were:

- Groundwater storage rights
- Basin judgments, adjudications, and management

⁶⁸ See Blomquist et al, *supra* note 17, at 45; Andres Sahuquillo, *Strategies for the Conjunctive Use of Surface and Groundwater*, in DROUGHT MANAGEMENT AND PLANNING FOR WATER RESOURCES 49, 50 (Joaquin Andreu et al. eds., 2006).

⁶⁹ *Id.*, Blomquist et al, at 25-26; Sahuquillo at 64.

⁷⁰ See *supra* note 32, 18. Working teams focused on ten competing priorities that represented “impediments to implementing a cost-effective conjunctive use water management program in California.”

- Area of origin for imported water and rights that may be transferred
- Stakeholder concerns over water rights
- Indemnification

Considering the above benefits/goals and associated legal factors, selected conjunctive use programs and some primary legal concerns in each state are reviewed. Table 4.2 lists explicit conjunctive program goals, legal issues, solutions associated with the goals, and program examples by state. There are far more programs than can be easily noted in a summary table. Thus, the table is intended as an example of conjunctive use development rather than an exhaustive listing of all possible programs. The comparison between programs in different states provides an indication of how conjunctive use can be a viable water management tool despite legal obstacles.

When surface water conditions are of primary concern, an early conjunctive program target was to supplement low surface water supplies with pumped groundwater. California has such a program in the agricultural region of Kern County, having used surface water for irrigation dating since the turn of the twentieth century.⁷¹ Not only were additional sources of surface water considered necessary to increase agricultural development, but after the 1940's groundwater was also pumped from aquifers in Kern County. Large-scale use of the combined water sources caused depletion of surface water supplies, and pumping triggered large drops in aquifer levels, land subsidence, and movement of inferior groundwater into the aquifer. The conjunctive program was expanded to address the problems. Surface water was imported through the Central Valley Project of which the Kern County conjunctive program was a part, and the aquifer

⁷¹ Jack J. Coe, *Conjunctive Use – Advantages, Constraints, and Examples*, 116:3 J. OF IRRIG. & DRAINAGE ENGINEERING., 439 – 442 (1990).

was artificially recharged through different water sources, to be “banked” and utilized in future needs. The Kern County program continues to the present day, using varied water management approaches to deal with the hydrological complexity of the region. The Kern County program is listed in Table 4.2 as an example conjunctive program to supplement low surface water supplies and also to reduce overdraft on an aquifer.

A second program included in Table 4.2 regarding supplementing water supply through groundwater, and of improving surface water quality, is that of the Canadian River Municipal Water Authority (CRMWA) in the Texas Panhandle. The CRMWA uses surface water from Lake Meredith, fed by the Canadian River, and groundwater from the Ogallala aquifer to provide water to member cities and industrial plants.⁷² Due to high concentrations of chlorides, sulfates, and total dissolved solids in water from Lake Meredith, mixing it with groundwater enables the CRMWA water supplies to meet state and federal water standards. Unfortunately, many recent studies have determined that groundwater levels in the Ogallala aquifer, which extends over four Great Plains states, have been significantly decreased through pumping. The groundwater system has become increasingly important as the lake’s reserves are quite low. In response, the CRMWA has aggressively pursued purchase of groundwater rights. As the CRMWA website does not include information about its conjunctive program, it may be that such lack of emphasis on conjunctive management reflects the importance in Texas water law of surface water and property rights.

As mentioned in the above discussions, reducing aquifer overdraft can be another key conjunctive program goal. In the CRMWA program, the Drought Contingency Plan

⁷² Otis W. Templer, *Municipal Conjunctive Water Use on the Texas High Plains*, 38 THE SOCIAL SCI. J., (2001) 597-604. In addition to general information about the CRMWA program, this paper provides background on the evolution of Texas water law and conjunctive use in the High Plains.

notes that surface water will be used to the extent possible so as to reduce impacts on “non-renewable groundwater resources.”⁷³ However, no other steps addressing the overdraft are noted. In California, the Kern County program and a long-term program in the Santa Clara Valley, now known as “Silicon Valley,” provide examples of aquifer overdraft reduction. Both regions experienced large volumes of groundwater withdrawn from a regional aquifer over the time, causing land subsidence and significantly decreasing aquifer levels.⁷⁴ These problems resulted in infrastructure damage and increased costs through increased pumping lifts in Santa Clara. The primary means of reversing the overdraft was to artificially recharge the aquifer through the use of “spreading basins,” which are areas of land set aside to allow water to percolate into the aquifer. The spreading basins are effective under the appropriate topographic and geologic conditions, although periodic maintenance is required. Recharged waters included irrigation return flows, imported surface water, and runoff. Land and aquifer levels have currently stabilized, however, allowing the program to focus on water supplies issues with continued population growth.

Several major groundwater basins along the Californian coastline have experienced seawater intrusion into aquifers, causing salinity degradation in groundwater and thus decreasing the available water supply for urban and agricultural needs. A case

⁷³ Canadian River Municipal Water Authority website downloads, *Drought Contingency Plan*, revised January 14, 2009, at [http://www.crmwa.com/Downloads/DROUGHT CONTINGENCY PLAN final.pdf](http://www.crmwa.com/Downloads/DROUGHT%20CONTINGENCY%20PLAN%20final.pdf) (last visited June 02, 2009).

⁷⁴ See *supra* note 68 (discussion of the Santa Clara Valley conjunctive use program with regard to general conjunctive use strengths and issues). Specific costs and benefits of the program are detailed by Eric G. Reichard & Robert S. Raucher, *Economics of Conjunctive Use of Groundwater and Surface Water*, in *WATER: SCIENCE, POLICY, AND MANAGEMENT*, AM. WATER RESOURCES ASSOC., WATER RESOURCES MONOGRAPH 16, 169-171 (2003).

in point is the Santa Clara-Calleguas basin in Ventura County.⁷⁵ As with other agricultural regions, the conjunctive system evolved over time in response to increasing area of irrigated acreage and crop needs. The system utilizes surface water diverted from the Santa Clara River, a natural recharge zone, and groundwater from wells located near spreading basins. The groundwater system has a lower and an upper aquifer; both have experienced seawater intrusion. As a long-term solution, hydraulic barriers were created through injection of non-saline waters through injection wells to appropriate depths in each aquifer. While the barriers have been effective in controlling the intrusion of seawater, continued groundwater pumping and the connection between surface water and the shallow aquifer ensure that the system will require conjunctive management of interactions between surface and ground water for the foreseeable future.

Development of water law in Colorado has had a direct bearing on a particular type of conjunctive management, augmentation of surface water supplies. The provisions of the 1965 and 1969 statutes that brought groundwater into the surface water prior appropriation system meant that groundwater rights are junior to many surface water senior rights. The relevant legislation was intended to clarify water rights throughout Colorado. However, groundwater pumping continued to expand, particularly in two major watersheds, the South Platte River which runs through Wyoming and Nebraska and Colorado, and the Arkansas River which extends from southeastern Colorado into Kansas.⁷⁶ Under the 1969 Act, groundwater pumpers in Colorado were allowed to

⁷⁵ See *supra* note 71, Reicher & Raucher. The conjunctive use system, operations, and model scenarios for evaluation of future seawater intrusion are detailed by E. Reichard, *Groundwater-Surface Water Management with Stochastic Surface Water Supplies: A Simulation Optimization Approach*, 31:11 WATER RESOURCES RESEARCH, 2845-2865 (1995).

⁷⁶ See Blomquist et al., *supra* note 23, at 673-680 (a concise overview of augmentation plans in the South Platte and Arkansas basins).

develop stream augmentation plans. These plans called for either decreed or temporary recharge of surface water to replace shallow water that migrated from rivers to pumping wells. Groundwater pumping associations began to acquire water rights. If the State Engineer's Office approved the augmentation plan, the association would submit annual estimates of how much groundwater would be pumped and how much water would be made available to the district for senior water rights.⁷⁷ These programs became known as "in-lieu" recharge, since the water made available to the district was provided in place of the water that was pumped. The seasonal pumping and seasonal calls for water mean that the basin's physical water system is not truly recharged but rather that water is made available for permit holders.

There are several large groundwater associations in the South Platte and the Arkansas basins. For example, Groundwater Appropriators of the South Platte (GASP) is one of the larger organizations, addressing the water requirements for thousands of well owners under the temporary and annual augmentation approach.⁷⁸ In recent years, however, drought has placed more restrictions on the quantity of available water, in Colorado as well as in the other two western states of the South Platte River basin. Thus, these annual water balancing actions may become more closely watched and questioned in regard to water rights.

A similar situation of highly-interconnected surface water and groundwater systems, conjunctive rules for surface water and groundwater permits, drought stresses on water availability, and recent water disputes characterizes Idaho's Snake River Plain. Irrigated crops were productive in the 1870's, and by 1905 the majority of surface water

⁷⁷ See *supra* note 23, at 675.

⁷⁸ See *supra* note 23, at 676.

was allocated under prior appropriation.⁷⁹ Canals were leaky, providing unintended recharge to the shallow aquifer. With increasing water diversions, groundwater recharge to the river increased as well, allowing many new surface water rights to be developed. Hydropower from dam and reservoir infrastructure also claimed additional surface water rights, as more wells were installed. Aquifer levels, tied to surface recharge and pumping, began to decrease in the 1960's. Groundwater was brought into the prior appropriation and permitting system during this time, and while permits were issued for surface and groundwater over the years, disputes increased in number with drought-induced decreases in water availability.

In 1994, IDWR adopted conjunctive administration rules for review and approval of surface and groundwater permits. After recent years of drought, concerns grew into a lawsuit involving hydropower agencies and other plaintiffs with senior water rights.⁸⁰ A primary concern was that pumping along the Eastern Snake River Aquifer prevented surface water permits from receiving full allocations, with IDWR requiring a curtailment of groundwater pumping. Eventually, the Idaho Supreme Court decided in favor of Idaho's conjunctive administrative rules, also finding that the rules did not disallow the prior appropriation system.⁸¹ Various modeling and participatory solutions are being tested for dealing with water disputes.⁸² However, it is likely that in the near future,

⁷⁹ See *supra* note 39, at 32.

⁸⁰ *American Falls Reservoir District No. 2 v. Idaho Department of Water Resources*, 143 Idaho 862, 154 P.3d 433 (Idaho 2007).

⁸¹ An informal legal summary of the court cases and decisions at the district and Idaho Supreme Court levels is made in Jeffrey C. Fereday, "Idaho Supreme Court Upholds Rules Governing Water Right Administration," in XL:2 ROCKY MTN. MINERAL LAW FOUNDATION WATER LAW NEWSLETTER (ed. George A. Gould), 1-7 (2007).

⁸² See generally Piotr Jankowski, *Towards Participatory Geographic Information Systems for Community-Based Environmental Decision Making*, 90:6 J. OF ENVIR. MGMT., 1966-1971 (2009); Donna M. Cosgrove and Gary S. Johnson, *Aquifer Management Zones Based on Simulated Surface-Water Response Functions*, 131:2 J. WATER RESOUR. PLANG. & MGMT., 89-100 (2005).

conflicts between water rights in the near future will continue if water rights were over-allocated under water-stressed conditions. Whether solutions such as Colorado's surface water augmentation or Washington's statutory and case laws that evolved into a stable water rights permitting system for surface water and groundwater will be attractive as partial resolution to Idaho's water battles, remains to be seen.

Aquifer storage and recovery (ASR) is another facet of conjunctive management. The premise is that of storing treated water in an aquifer with identified and well-known characteristics such as geologic matrix, accessible volume, the number and nature of multiple layers, recharge area and discharge points, and anticipated well withdrawals. The stored water may be imported surface water, treated wastewater, or water from another source, typically injected through the same well or wellfield used for withdrawals. A key part of the system is treatment of the water prior to its sub-surface injection so that use of the ASR system will not degrade the aquifer or its natural groundwater. An ASR system may take some years to characterize, test, define its limits, and implement, much less permit. Legal factors center around rights to store and retrieve water, the injection facility and permit, and ensuring no resulting degradation of the aquifer.

ASR systems are used by several municipal water districts in California. One example project is operated by the Calleguas Municipal Water District (MWD), which also has a conjunctive use project targeting seawater intrusion (see Table 4.2). The Las Posas ASR is operated in partnership with the Metropolitan Water District of Southern California (Metropolitan).⁸³ The project design supports the storage of treated water

⁸³ The Los Posas Basin conjunctive use project is generally described in the Calleguas MWD brochure, at <http://www.calleguas.com/projects/lpbroc.pdf>.

from Metropolitan in the Las Posas ASR for withdrawal during low water supplies. The program is an example of regional cooperation between agencies and the benefits of storing treated water in an appropriate aquifer, while allowing withdrawals during critical times to support users over a larger region.

A program in central Texas operated by the City of Kerrville also illustrates the utility of ASR.⁸⁴ The city and regional river authority developed the program in response to greatly-lowered aquifer levels during droughts. The overall goal was to obtain more reliable water supplies. During studies of possible reservoirs, it was determined that aquifer characteristics would be supportive of storing injected water for retrieval at future times.⁸⁵ The ASR system has operated since the mid-1990's, is being considered for expansion through the regional water planning process, and is considered a strong factor in providing water to the city during future low water supplies.⁸⁶

Conclusions and the Legal Future of Conjunctive Use

This study reviews basic water law of selected states in the western United States and provides a comparative analysis of conjunctive use under different state's legal systems. The five states, California, Colorado, Idaho, Texas, and Washington, were selected as examples of similar yet differing legal systems in the western United States. Each state has variations of conjunctive use as a water management approach.

⁸⁴ The ASR is a critical part of drought management as well as water supply for the City of Kerrville; see the Public Water System update at <http://www.kerrville.org/index.aspx?NID=807> (last visited June 18, 2009).

⁸⁵ The project background includes development of the ASR through the regional river authority, the Upper Guadalupe River Authority (UGRA) in addition to the City; see Jim Brown, *UGRA & Conjunctive Water Mgmt. Practices*, in WATER FOR TEXAS' FUTURE: THE LEGAL ISSUES, 2ND ANNUAL TEXAS WATER CONSERVATION ASSOCIATION/TEXAS RURAL WATER ASSOCIATION WATER LAW SEMINAR, Austin, Texas, (January 24-25, 2002). The presentation notes include two lawsuits brought against use of the ASR, making it one of the few systems in the U.S. to be contested, according to R. DAVID G. PYNE, *GROUNDWATER RECHARGE AND WELLS: A GUIDE TO AQUIFER STORAGE RECOVERY*, CRC Press, Inc., (1995), 307.

⁸⁶ See *supra* note 83.

The prior appropriation system is a keystone of western U.S. water law and is a fundamental fact of water law for the five states under review. “First in time, first in right,” an informal expression that succinctly describes prior appropriation, has supported many decades of economic growth and development of cities through secure water rights in arid to semi-arid regions in which rivers do not necessarily flow throughout the year. Although the riparian doctrine was initially used in the mid-nineteenth century; however, it did not fit the geography and watersheds of the West. Today, riparian rights are few, while appropriative rights and surface water permits are overwhelming the rule applied to surface water rights.

Groundwater rules evolved more slowly, first as technology allowed installation of wells and pumps, then in response to changes in surface water supplies. Thus, states took different approaches to groundwater laws. California has a multi-faceted system, including “subterranean” groundwater considered to be part of surface water bodies and correlative rights for “percolating” groundwater, pueblo rights that take precedence over appropriative rights, and a new approach to waters of the state under the public trust doctrine. In Colorado and Idaho, placing groundwater within the surface water permitting system has not precluded legal challenges to senior and junior water rights. Washington also experienced legal disputes after the 1949 legislation that began conjunctive administration of surface and ground water. Over the decades, however, the system appears to have evolved such that permitting a subsurface source is anticipated, rather than disputed, to consider effects on the surface water bodies. Texas addresses rights to groundwater as fairly close to property rights, with some limitations.

Notably, none of the states' water law systems explicitly forbid conjunctive use, although the legal framework can discourage conventional conjunctive use.⁸⁷ Some state laws are more supportive than others. The earliest conjunctive use research and implementation was in California;⁸⁸ therefore, many of the initial legal disputes have been worked through over the decades. Colorado's legal system encourages augmentation of surface water supplies from groundwater pumpers, having been in place in major watersheds since the 1970's. Whether augmentation plans in Colorado or new conjunctive administration rules in Idaho will continue to support water needs in the future without major legal challenges, particularly during water-stressed periods or with regard to the water needs of competing state interests in interstate rivers such as the South Platte, is not known.

Other factors may be more important to the viability of a conjunctive use program than a state's legal system. As noted, the approach requires an appropriate physical system of surface water bodies and aquifer(s). While theoretical economics has offered strong proofs of conjunctive use's efficiency, the socio-economic conditions of a given region may preclude use of the approach. The social perspective of stakeholders is also critical, particularly for future programs in contrast to well-established programs. All four components of conjunctive management – physical water systems, economics, societal support, and legal framework – provide a necessary foundation for viable conjunctive strategies. The following chapters demonstrate, however, that additional components provide a more complete understanding of conjunctive management and its applications to water resource management in the future.

⁸⁷ See *supra* note 69.

⁸⁸ See *supra* notes 1, 2.

This research into water laws and doctrines in the western United States illustrates that a legal framework does not tend to preclude implementation of conjunctive use in regions where it has not heretofore been utilized. Conjunctive use programs can and have flourished under different water law and permitting systems, as well as under different physical conditions. The program goals noted in Table 4.2, versus major legal concerns and actions taken, are a sure sign of the flexibility of conjunctive use and its application to various water supply issues. As the western United States continues to experience population growth, concomitant with agricultural and industrial demands, the conjunctive use approach may become increasingly important and attractive in balancing water supplies for regions and water districts.

Table 4.1 Water Doctrines and Rules in Five Western States

State	Category	Classification	Surface Water Doctrine		Groundwater Rules			Rules Applicable to SW & GW		
			Prior Appropriation	Riparian	Permit Required	Correlative Rights	Permit Exempt	Pueblo Rights	Public Trust	Conjunctive Administration
California	SW		✓	✓				✓	✓	
	GW	Subterranean	✓	✓	✓			✓	✓	
	GW	- Percolating, overlying lands				✓ 1				
		- Percolating, surplus water				✓ 1				
Colorado	SW		✓ 2							
	GW	Tributary	✓ 2		✓					
		Non-tributary	✓		✓ 3		✓ 3			
		Designated basin	✓ 2		✓ 3					
Idaho	SW		✓ 4							
	GW	State GW			✓ 4					
		Water district			✓ 2,4		✓ 4			
Texas	SW		✓							
	GW	GW authority			✓ 2					
		GWCD, UWCD			✓ 5	✓	✓			
		Other					✓ 5			
Washington	SW		✓	✓ 6						✓ 6
	GW						✓ 6			✓ 6

SW – surface water

GW – groundwater

GWCD – groundwater conservation district

UWCD – underground water conservation districts

Table 4.1 continued

Notes on Permits and Exemptions:

- 1 – In California, percolating groundwater may be used by overlying land owners on their lands, within the correlative rights shared by all landowners overlying the aquifer. If correlative use doesn't exceed the aquifer's yield, then "surplus" groundwater can be appropriated by non-overlying water users or suppliers. Surplus appropriation is subordinate to correlative rights.
- 2 – Special district permitting. In Colorado, there are seven water districts, each with its own water court and adjudication process. In Idaho, districts such as the Snake River Plain have been defined. The Edwards Aquifer Authority, the Harris-Galveston Coastal Subsidence District, and the Fort Bend Subsidence District are special water districts in Texas with legislated requirements for groundwater permitting and withdrawal limits.
- 3 – In Colorado, both surface water and groundwater rights can be either absolute (a right adjudicated through a water court, and appropriated for beneficial use), or conditional (a project-specific right to develop future beneficial water use). Every water right must have a point of diversion. groundwater is considered tributary to surface water unless proven in water court to be non-tributary under rigorous specifications. Water allocation from non-tributary aquifer is based on percent of land owned above aquifer. Wells that pump less than 15 gallons per minute may apply for exemption from the priority system.
- 4 – Idaho has a statewide permitting and allocation system whereby surface water and groundwater are managed separately, but each permit must consider the effects that the water diversion and use may have upon surface water and groundwater. Idaho exempts "instream livestock use" and "domestic purpose" water from permitting. These uses must total less than 13,000 gallons per day (gpd), or a diversion rate of 0.04 cubic feet per second and total diversion volume of 2,500 gpd.
- 5 – Texas district rules for well permits vary among the current 98 groundwater conservation districts, depending upon each district's enabling legislation. Wells outside of a groundwater conservation district or an aquifer authority are typically exempt from regulation. Exceptions are rules that require pumped water to be beneficially used and not wasted; landowners may not pump groundwater so as to deliberately cause harm to an adjacent landowner; well owners may be held liable for groundwater pumping that cause land subsidence.
- 6 – Washington State has a statewide permitting system for surface water and groundwater, or conjunctive administrative. The state has early water rights vested in the riparian doctrine as well as rights through prior appropriation. Through case law, riparian rights were lost if not put to beneficial use, resulting in gradual change of most riparian rights into the prior appropriation system. Washington allows permit exemptions for livestock use, residential water up to one-half acre, domestic use up to 5,000 gpd, and limited industrial or irrigation use up to 5,000 gpd.

Table 4.2 Goals, Legal Factors, and Programs

Conjunctive Use Goals	Legal Factors	Actions	Program Examples				
			California	Colorado	Idaho	Texas	Washington
Supplement low surface water (SW) supplies with groundwater (GW) or other sources	<ul style="list-style-type: none"> • Import SW • GW rights 	<p>CA: import SW & create water districts and water banking; artificial recharge</p> <p>TX: purchase or lease overlying land for the right to pump & transport GW</p>	Kern County			Canadian River MWA	
Reduce aquifer overdraft	<ul style="list-style-type: none"> • GW rights • Import SW 	<p>CA: Create regional water authority; approved artificial recharge via spreading basins using different water sources</p>	Kern County; Santa Clara Valley				
Hydraulic barriers to seawater intrusion	<ul style="list-style-type: none"> • GW rights • Degradation of aquifer 	<p>CA: Create regional water authority; levy tax to buy SW for AR & delivery to purveyors; allow injection wells</p>	Santa Clara-Calleguas basin				
Augment SW supplies during low flows through “in-lieu” recharge	<ul style="list-style-type: none"> • Senior SW rights keep priority over junior pumping rights 	<p>CO: GW pumping groups acquire water rights, place under control of State or District Engineer for release to senior rights’ calls</p>		GW pump assoc. in water districts			
Apply conjunctive administration rules to SW & GW permits	<ul style="list-style-type: none"> • Primacy of appropriative rights or conjunctive administration 	<p>ID: Supreme Court upheld administrative rules; if waters are over-allocated, challenges are probable during droughts</p> <p>WA: Statutory & case law established statewide water rights system</p>			Eastern Snake River Aquifer	All state water permits	
Aquifer storage & recovery (ASR)	<ul style="list-style-type: none"> • Right to inject, store, & withdraw treated water from aquifer • Ownership 	<p>CA: Municipal programs supplement water supply</p> <p>TX: Municipal need for water supply, drought mitigation; first operated by regional distr., city</p>	Calleguas MWD – Las Posas ASR			Kerrville ASR	

Canadian River MWA – Canadian River Municipal Water Authority, based at Sanford Dam, about 37 miles northeast of Amarillo, Texas.

CHAPTER 5

SOCIAL AND STAKEHOLDER INTERESTS

Water supply and management decisions at the present time require more information than planning and decisions of 50 years ago. Not only are technical, geographical, and demographic factors considered throughout water management decisions, but present-day concerns of a region's society are also considered critical to successful, long-term water management strategies and programs. Conjunctive management of surface and groundwater supplies is no exception to these concerns. Identifying socially-based factors, however, requires techniques that allow evaluation of qualitative and quantitative elements. This chapter discusses such evaluations and their results with respect to social/stakeholder inputs concerning conjunctive water management.

Background

Factors that inform, control, and ultimately determine the degree of success of conjunctive water use programs are known to include four primary components - the physical water systems, legal issues, economic input, and social factors involved within a region (Maknoon and Burges 1978). Of these components, research studies consider one or two components, but rarely all four. A water balance study, for example, may emphasize the timing of available water sources over a year, how surface water and groundwater interact, and alternative water balance for withdrawals, thereby addressing

the physical water systems of that region. An alternative perspective based on the physical system components, an economic study may model the effectiveness of one water source over another, thus addressing two of the four components. Selected examples of economically based approaches are found in a study design to operate a reservoir and aquifer for agricultural purposes (Buras 1963), a study regarding optimization of operations optimization for agricultural and urban uses (Noel et al. 1980), and an evaluation of conjunctive use through hydrologic and economic approaches (Reichard and Raucher 2003). Studies have also integrated several components and multiple variables of conjunctive management in water balance models, thereby allowing decision-making at a more complex level (Booker et al. 2005; Cai et al. 2003).

Although few research studies focus on the social or stakeholder component of conjunctive use, conjunctive programs recognize the importance of this aspect and incorporate social concerns into the program. Societal and stakeholder concerns, among other technical, political, legal, and institutional issues, were identified in a 1998 workshop in California about conjunctive use (NWRI 1998). In 2001, California's Department of Water Resources established a partnering program, the Conjunctive Water Management Branch, to aid regions and groundwater basins of the state to initiate, or expand, conjunctive use programs (CDWR 2009). A review of the summaries of the 18 partnerships' identified stakeholder concerns common to many of the regional conjunctive use programs, including planning, monitoring, and facilitated stakeholder outreach.

To better understand societal concerns, issues, and perspectives of conjunctive management as an approach within itself, rather than within the context of one specific

region or water management program, an online survey and interviews with water management professionals were carried out over 18 months during the course of this research. The results address the gap in knowledge over social and stakeholder interests and allow additional perspective on this component of conjunctive management.

Methods

The survey was designed with quantitative and qualitative, or objective and subjective, factors in mind (Tashakkori and Teddlie 1998). The content and questions were formed from publications, websites, and discussions among colleagues. Due to the specialized nature of the topic, the survey questions were designed for water management professionals. The design was purposeful and targeted toward a non-random group, thereby using the “stratified non-random sampling approach” (Tashakkori and Teddlie 1998). The survey was created using online tools through an online survey management company. Questions were separated into sections concerning water resources background and general management and operations of conjunctive use programs, surface water and groundwater; economic benefits and costs, laws and institutions, and viability of conjunctive use programs.

The survey was forwarded to experts or researchers in water agencies and conjunctive use programs or with related experience in water law, economics, hydrology, or hydrogeology. The experts were identified through peer-reviewed publications and website information. Because water managers and other experts had a wide variety of backgrounds and experience, the survey’s design allowed respondents to skip sections that they did not feel qualified to answer. The River Systems Institute of Texas State

University-San Marcos (Texas State) kindly allowed the author to send the survey link through their email address.

A key feature of the survey was that the tally of results would not keep nor track the computer identification codes of any survey respondent. Because the survey used procedures in which responses would not be linked to respondents, the research was exempted from full review under 45 Code of Federal Regulations, Part 46, Section 101(b) (Texas State University-San Marcos Institutional Review Board 2007a). The survey was prepared, submitted, and collated in 2007; the results were analyzed in summer 2008.

A low number of survey responses, 13 out of 92 requests or a 14 % response rate, prompted a second phase of collecting information and data about social and stakeholder interests in conjunctive use based on informational interviews conducted with water management professionals. The survey results provided a starting point for compiling a focused list of interview topics and questions. The list of interviewees was based on persons identified during the survey contact search, colleague recommendations, web searches, and closeness of fit between the person's professional experience and conjunctive use. Interviews began with the outlined questions and topics but diverged slightly, as necessary, so as to take advantage of each expert's background and their current research or conjunctive use project. The interviews were conducted under exemption authorized by the Texas State University-San Marcos Institutional Review Board (2007b).

Online Survey Responses

Analysis of the survey was conducted in accordance with the number of responses per question (respondents were allowed the option to respond, or not respond, to all but

two questions), responses that included a high-to-low rating, and whether the responses were objective and definitive or subjective in nature.

Of the 92 survey invitees from 20 U.S. states, 13 responded, resulting in 14% overall participation. The number of responses per question varied from 0 to 13. This participation level was considered too low to allow adequate parameterization of the data or inferential projections. However, the responses allowed some insights as to key conjunctive use issues and provided directional feedback for future interviews.

The survey summary report is shown in Appendix B. Using this summary report in conjunction with the data report and open-ended responses, a summary table was prepared (Table 5.1). Per topic, this table lists the items of inquiry, summarized results, and ratings. The following subsections discuss highlights of the survey results.

General Management and Operations

The initial survey section requested information about location of general conjunctive use operations with which the respondents were familiar. The states in which the respondents utilized conjunctive use were Arizona, California, Illinois, New Mexico, Texas, and Rhode Island. Responses indicated that the programs typically operated under state-authorized special water districts, irrigation districts, or municipalities. However, special cases included adjudication, court-appointed watermasters, joint-power authorities, and federal agency research programs. The highest rated water uses were municipal and agricultural, while the lowest rated were industry and specific habitat flows. Based on the number of responses, the duration for growth in conjunctive use programs varied, depending upon the stage of growth. Planning activities might take about 6-10 years; construction and implementation about 1-5 years; operations growth

about 11-20 years; and phase-out more than 50 years. Background and years of training for persons working in conjunctive use appeared to vary among scientific, engineering, and business disciplines.

Regarding accessible water rights for various water sources, rivers and aquifers greater than 100 feet were the top selections, while natural lakes or imported groundwater sources were the lowest rated. The approximate operating budget of a typical conjunctive use program was typically judged “unknown,” though some responses indicated such a budget may be between \$100,000 and more than \$1 million annually.

Surface and Ground Water Information

Surface and ground water information deemed necessary to develop conjunctive use models included basic flow parameters and volumetric changes over time. Monitoring takes place at those locations already established for other water management programs, including flow gauges along rivers and wellhead meters. Selected software programs are in current use in the United States (MODFLOW or RiverWare). Typical storage capacity or groundwater pumping might vary from 100 to 10,000 acre-feet per year (AFY). From a hydrologist’s or hydrogeologist’s perspective, possible triggers for conjunctive use programs that might be used to signal the cessation of use of one water source and initiate the use of another could be when surface water flows decrease below program-defined levels, or the water price increases above a program’s target.

Economic Benefits and Costs

Survey responses included the potential for increased water availability and drought mitigation as a possible major benefit for conjunctive use. Lower rated benefits were the potential for increased water conservation and flexible water prices.

Conversely, possible major costs were deemed to be neutral. Moreover, the costs of conjunctive use may be lower than those of alternative water management programs. Pricing structures that might support efficient water allocations were seasonal or variable rates, whereas block or uniform rates were considered less efficient. Economic incentives were perceived to be effective in conjunctive use, including subsidies to cover the price differential between surface water and groundwater. However, respondents did not consider price markups to be an effective inducement to conserve water.

Law and Institutions

Questions about laws that support conjunctive use resulted in a high rating for prior appropriation of surface water and low ratings for beneficial use and equitable apportionment. No groundwater rule of law was considered supportive of conjunctive use, and a low rating was given to rules based on historic uses of groundwater. Under transboundary water considerations, a high rating was given for physical differences in water sources across geopolitical boundaries, while the low rating was defined by differences in water laws across geopolitical boundaries. The manner in which government institutions support conjunctive use programs were also found primarily at state agencies through grants and water permit support, and at municipalities through direct funding and organizational framework.

Viability of Conjunctive Use Programs

When queried about water availability in the program with which the respondents were most familiar, most respondents indicated that water availability had not significantly changed in the last 10 years. For programs that experienced a decrease in water availability, a low rating was chosen for basin-wide droughts or declining

groundwater levels. Measurable changes in water conservation were generally unknown. Setbacks to viable conjunctive use included differences in legal frameworks for surface water and groundwater, while a lesser rating for setbacks includes decreasing groundwater levels, decentralized water agency oversight, legality under state rules, and a lack of coordinated basin oversight. Finally, responses as to whether conjunctive use should be included in future federal or state water supply plans were yes (high rating overall) and no (low rating). The positive responses gave the following reasons: (i) conjunctive use addresses a number of water supply problems; or (ii) it provides an often-low-cost source of “new” water to address water shortages and availability. The negative response noted the site-specific nature of such programs and the inherent difficulties of involving conjunctive use at state or federal planning levels.

Evaluation of Survey Results

The responses indicate that general indicators of viable conjunctive use programs may be found in a variety of climatic regions and states. Water sources for the programs are most likely to be rivers and accessible groundwater. Conjunctive use programs are likely to continue throughout a period of more than 50 years. A variety of technical and professional expertise is recognized in managing conjunctive use programs, and the operating budgets may compare favorably to alternative water management strategies. Although the low number of respondents does not allow projections of the data, analysis of the results provides several points for consideration in future conjunctive use planning as follows:

- Conjunctive use appears to be most successful in long-term planning and management of large-scale water demands, particularly agriculture and municipalities.
- Oversight authority for conjunctive use programs may be best placed with water or irrigation districts, which have information about local water user issues and site-specific details critical to successful water management.
- Possible benefits include drought mitigation, but not necessarily water conservation.
- Costs of conjunctive use program operations can be lower than those of alternative programs.
- Transboundary issues may involve physical differences in water sources.
- A primary setback in planning a conjunctive use program can be differences in legal frameworks for surface water and groundwater.
- There are substantial arguments for and against inclusion of conjunctive use in future water supply plans.

The online survey provided sufficient feedback to suggest key factors in successful conjunctive use programs. To better understand conjunctive use programs that are currently active and how conjunctive use/management may be perceived by experts in different water resource disciplines, the survey results were used in preparing interview questions, the results of which are discussed in the following section.

Interview Results

During 2008-2009, interviews were conducted in person or via telephone with selected water resource professionals. Each interviewee was contacted by email or phone

to explain the goals of the research project and to request 20-30 minutes of their time. From contact through scheduling to the actual interview typically took 1 to 3 weeks. Prior to each interview, the water professional's background, current research or professional projects and publications were reviewed by this researcher. Emphasis was placed on the water professional's interests and projects in each interview; thus, no two interviews were alike. If the interview came close to the 30-minute timeframe but the interviewee was willing to continue beyond the 30-minute timeframe, the discussion was continued. The basic interview format is shown in Appendix C.

The goal of these interviews was to find insights regarding current views on conjunctive management and knowledge about current implementation strategies. Notes from each interview were reviewed and coded in accordance with grounded theory approaches (Strauss and Corbin 1998). Major items reviewed in the context of an overall understanding of conjunctive use, its applications, and issues, were 1) the interviewee's understanding of conjunctive use; 2) conjunctive use-type projects with which they were involved; and 3) the interviewee's perspective on his/her most critical water management issue for the next 20 years, as well as recommendations for the best solution in the same time frame.

The interviewees were from the following industries and research fields: water management, surface water and groundwater modeling, water law, industry and government affairs, environmental non-government organizations (NGOs), state and federal positions, research in economics, and research in hydrology. The interviewees worked in California, New Mexico, and Texas. Twelve interviews were conducted and analyzed with the results discussed in the following section.

Definitions and understanding of conjunctive use varied among the interviewees, while two interviewees did not have a ready definition. Some interviewees understood the term to indicate the use of more than one source of water. Those actively involved with conjunctive use projects noted that the term also included management and/or optimization of water sources and possible impacts on those sources.

Conjunctive use-type projects were not alike for any of the interviewees.

Water resource modelers discussed their experiences with developing conjunctive use-type models, though the goals often were not conjunctive use. In each case, the modeling approach was different, reflecting the project's goals, the modeler's background and experience, the local hydrology and aquifer characteristics, and available data.

The legal expert dealing with water law worked with clients whose primary concerns were water availability. Thus, the project focus was on obtaining water rights through surface or groundwater. Rather than being a goal or water management strategy, conjunctive use was a side result of the process of obtaining legal water rights.

Persons dealing with water management issues in government and NGO positions did not have specific conjunctive use projects, but were familiar with the possible impacts of conjunctive use. The overriding concern for these persons was not whether conjunctive use should be implemented, but rather how to minimize the impacts of any water management approach on future water supplies and the environment.

Professionals working in active, current conjunctive use projects focused on the importance of an aquifer's storage function. In terms of the legal framework, historical precedents, diversions, and infrastructure, western U.S. water management is better

defined for surface water allocations than for groundwater allocations. Therefore, these interviewees emphasized that a particular strength of applied conjunctive use is groundwater storage, particularly if waters are stored for times of drought. They also noted difficulties in implementation of groundwater storage and recovery due to a state's rules on groundwater, permits, and interbasin transfers of water.

The topic of critical water management issues for the next 20 years covered a range of issues. Notably, none of the interviewees suggested that there are, or will be, no problems in water management. Discussed issues and suggested solutions included:

- Hydrologic, hydrogeology, and economic modeling: The simplest level at which a model can function and address the questions asked should be the starting point. Permitting, institutional requirements, and cost factors play a role in whether a technically feasible model can be implemented.
- Government and NGO water managers: A difficult question is how to limit groundwater pumping to sustainable limits in order to ensure future water supplies and minimize impacts on the aquifers and associated systems. If few regulations are in place to limit pumping, then future supplies may have to come from conservation and reuse rather than new surface water and groundwater sources. Local and regional control of groundwater is one key to getting shareholder "buy-in."
- Industry government affairs: There are limits on the quantity of available water, and these are understood to be highly emotional issues. Because all persons need and use water; therefore, the solutions must be found with all relevant parties having a role at the table.

- Economics and agricultural research: During times of crisis such as drought, agricultural water rights are increasingly taking a second place to municipal water demands. The biggest issue is water availability, particularly in light of potential climate impacts. For an economist, one solution is to use price ranges. If the marginal cost increases to a certain marginal use, then people can pay more or choose to use less water. For agriculture, choosing to use less water within current water application systems may not be possible without loss of crops.
- Experts with active conjunctive use projects: The most critical problems are developing water management choices for water management that have an established legal basis in water rights for the project. Such a basis is needed for aquifer storage and retrieval projects as part of conjunctive use strategies. Solutions can involve education outreach, financial incentives, and permitting.

The interview results highlight the disparity with which conjunctive management is perceived and implemented. The basic concepts are fairly well agreed upon, but conjunctive use in New Mexico and Texas does not seem to be utilized to its full potential as a water management strategy. Not surprisingly, interview results with two persons actively working in conjunctive use projects indicated that these experts had the greatest understanding of the strengths and weaknesses of planning and implementing conjunctive use as a water management resource tool. The flexibility of the approach is one of its strengths – conjunctive use can be applied in different geographic regions, different surface water systems and aquifers, and differing legal frameworks, albeit within limits. These persons expressed technical knowledge about two separate designs

incorporating conjunctive use, issues overcome during implementation, and enthusiasm for the strengths that conjunctive use can bring to water management.

Strengths and Weaknesses of the Survey

Conjunctive use has four primary components, identified through research studies and active programs, which require some consideration during program planning and implementation. Of those components, the least studied is that of societal and stakeholder interests and issues. To better understand those issues, a survey of water managers and researchers around the United States was undertaken, followed by person-to-person and phone interviews with water management professionals in California, New Mexico, and Texas.

Both the survey and the interviews provided insights into perceptions not only of conjunctive use, including differing responses over what exactly is entailed in a conjunctive water program, but also about water management. More than any other indicator, the evaluation results illustrated that every professional had a different opinion on the definition, uses, and application of conjunctive use. If the professionals do not agree on the basics of conjunctive use, it is unlikely that water policy-makers and stakeholders will understand whether it is a viable option for future water management decisions.

A weakness of the survey and interviews was the small data set of responses. For the survey, the stratified, non-random population of less than 100 persons was necessitated by the realization in preparing the survey questions of how few people have an understanding of conjunctive use. A similar point was made for the interviews, that of requiring familiarity with aspects of water management, in addition to the willingness to

be interviewed (and give up one's professional time) about a subject that is not easily covered in less than 30 minutes. Thus, it was recognized that development of the population database for the survey and interviews required persons with some knowledge of water management approaches. The result was a fairly small population for the survey and interviews. As an explanatory note about the survey, a rule of thumb is that a 10% response is considered adequate. While the number of respondents compared to the total number of survey requests resulted in a 14% response, this baseline number does not reflect the very low number of responses, including none, to all questions. Therefore, the quantity of parametric data generated by the survey responses was considered much too low to allow data projections.

Future research in this area will require a much larger population for a survey and fewer but more targeted questions for both the survey and interviews. Overall, the study was considered to provide much-needed insights and feedback from water management professionals. One additional benefit of the feedback is that the questions and responses allowed inclusion of social and stakeholder concerns into creation of a framework for conjunctive management decision-making. Along with a framework of the other three primary components of conjunctive management, the social and stakeholder concerns are incorporated into a conjunctive strategy decision framework in Chapter 6 of this dissertation.

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Table 5.1 Survey Topics, Responses, and Ratings

Survey Topics	Response Summary	High Rating	Low Rating
<i>General Management and Operations of Conjunctive Use (CU) Programs</i>			
States of respondents' CU programs or research	AZ, CA, IL, NM, RI, TX		
Authority for CU program		Water districts, special districts	Federal agencies
Water uses in respondents' CU programs		Municipal, agriculture	Industry, habitat flows
Stages of CU program longevity			
- Planning		6 - 10 years	> 20 years
- Construction and implementation		1 - 5 years	> 20 years
- Growth of operations		11 - 20 years	1-5 years; > 50 years
- Phase-out		> 50 years	< 1 year
Experience and training for persons in CU	Civil or agricultural engineering, soil science, hydrology, hydrogeology, business management, water law, economics/finance; unknown	Background or training information unknown	
Accessible water rights for water sources	River diversion, reservoir, offsite channel, shallow (<100 feet) aquifer, deep (>100 feet) aquifer, imported surface water, treated wastewater	Rivers and shallow aquifers	Natural lake; imported GW
Approximate annual operating budget		More than \$1,000,000 AND "information not available"	< \$100,000
Respondents' expertise/training	Government water agency/district (4), CU program mgt (1), research in SW/GW (3), research in water law (1), research in natural resource economics (4)		
<i>Surface and Ground Water Information</i>			
Aquifer characteristics	Confined and unconfined		
Monitoring of water resources in CU programs	Surface water (flow gauge) and groundwater (wellhead meter)		

Table 5.1 continued

Survey Topics	Response Summary	High Rating	Low Rating
<i>Surface and Ground Water Information (continued)</i>			
Monitoring of water resources in CU programs	Surface water (flow gauge) and groundwater (wellhead meter)		
Significant hydraulic characteristics in CU program's water balance model	Flow, rainfall, evapotranspiration (ET), reach length, channel (width, slope, loss/gain), hydraulic conductance, roughness coefficient	Flow, rainfall, ET, conductance	Water quality
Significant groundwater characteristics in CU program's water balance model	Aquifer geometry and matrix, hydraulic conductivity, storage, leakage, well discharge over time, water quality	Aquifer geometry, hydraulic conductivity, well discharge over time	Spring conductance
Software choices for a new CU model		MODFLOW with stream module, RiverWare	HEC-HMS, artificial neural networks, DHI MIKE Basin
Typical range of storage capacity for CU program's water sources	River or imported SW: 100-10,000 acre-feet per year		
Typical range of pumping for CU program's groundwater sources	Wellfields: 100 - 10,000 acre-feet per year		
"Trigger" to define move from program use of 1 water source to another	Surface water volume decreases below program-defined target level; water prices increase above program target		
<i>Economic Benefits and Costs</i>			
Major benefits of CU programs		Increased water availability; potential for drought mitigation	Potential for increased water conservation; flexibility in water prices; potential for drought mitigation
Major costs of CU programs	Respondents perceived costs to be neutral overall.	Costs are lower than those of alternative water mgt programs	

Table 5.1 continued

Survey Topics	Response Summary	High Rating	Low Rating
<i>Economic Benefits and Costs (continued)</i>			
Pricing structures that support efficient water allocation in CU programs		Seasonal or variable rates	Block rates
Are economic incentives effective in CU programs? If so, which incentive(s) are most effective?	Yes	Subsidies to cover the price differential between surface water and groundwater costs	
Do price markups encourage water conservation by users in CU programs?	No		
<i>Laws and Institutions</i>			
Surface water law that supports CU programs		Prior appropriation	Beneficial use, equitable apportionment
Groundwater law that supports CU programs		None	Historic use
Considerations in transboundary water programs		Physical differences in water sources	Differences in water laws across geopolitical boundaries
How do government institutions support CU programs?	State: grants, water permit support. Municipal: direct funding, organizational framework		
<i>Viability of Conjunctive Use Programs</i>			
Has water availability in your CU program decreased in last 10 years? If yes, why?		No	Yes: basinwide drought conditions; declining GW
Has the CU program with which you are familiar experienced change in water conservation? If yes, approximately how much change?		Unknown	Yes: increase in conservation by 6-10%

Table 5.1 continued

Survey Topics	Response Summary	High Rating	Low Rating
<i>Viability of Conjunctive Use Programs (continued)</i>			
Applicable setbacks to viable CU		Differences in legal framework for SW & GW	GW level decreases; decentralized water agency oversight; legality of CU under state rules; lack of coordinated basin oversight
Should CU be included in future federal or state water supply plans? Why or why not?		Yes: "CU does address a number of water supply problems that are usually addressed by more expensive and environmentally damaging projects." "CU provides a valuable, often low-cost source of 'new' water." "CU addresses water shortages." "CU addresses water availability."	No: "CU is so site-specific that there is little to be gained by trying to include it at state and federal levels."

Notes:

CU – conjunctive use

GW – groundwater

SW – surface water

CHAPTER 6

FRAMEWORK FOR CONJUNCTIVE WATER STRATEGY DECISIONS

Basis for Proposed Platform

Previous chapters focus on the basics of conjunctive use and four major components that influence its success as a water management tool. Analysis and where possible, parameterization of the four components (physical surface and groundwater systems, economic efficiency, the legal basis, social and stakeholder perceptions) provide a starting point for considering conjunctive management. However, in-depth evaluation of the components also indicates that a cohesive approach to designing and implementing a conjunctive strategy, regardless of location and legal framework, is lacking. Therefore, this chapter proposes a new conjunctive strategy framework to initiate future conjunctive management programs.

To reiterate previous conclusions, each component of conjunctive management provides fundamental information and support to conjunctive approaches. Under the current complexities and linkages between water management, physical setting, population of water users, and legal framework, utilization of any single component is not sufficient to warrant a successful, long term management approach. In Chapter 2, the evaluation of physical conjunctive water systems demonstrates a wide variation in water systems and characteristics. Rather than negating or narrowly defining conjunctive

approaches, the broad and extensive range of applicable settings demonstrate viable conjunctive strategies in many geographic locations. Theoretical economic studies prove efficiencies inherent in conjunctive management, while applied research demonstrates effective resource management through use of optimization and modeling. Analysis of economic-conjunctive use models in Chapter 3 defined common parameters in conjunctive use strategies regardless of location, as well as unique parameters that support and better define the strategy. Chapter 4 documents the strategy's legal basis in five western U.S. states. Conjunctive use/management does not lack a legal basis. On the contrary, broad legal support exists, only differentiated by specific legal cases and resolutions, state by state. Chapter 5 demonstrates societal views on conjunctive use via survey and interviews. The results illustrate the disparate views and understandings of conjunctive use. Even though conjunctive strategies have been researched and applied in many U.S. states and across the world, there is little agreement on definition, strategic approach, and appropriate applications. A new conceptual model is needed to address these gaps, and a new planning approach is necessary to implement the concepts, regardless of geographic location.

In this research, key elements of conjunctive management are addressed through the development of a "framework" composed of a conceptual model, key criteria, and decision matrix. The approach recognizes the importance of both the quantitative and qualitative aspects of any water management decision for the present and future. While quantitative data and models provide vectors and defined directions for physically answering water supply and demand, the qualitative aspects allow a working, adaptive context within which water management may be successful for years to come. Both

quantitative and qualitative aspects are necessary to future conjunctive strategies and are incorporated in the framework.

Previous Research

Over the decades, an extensive body of literature and research on conjunctive use has been established, including systems analysis, case studies, and framework documents. Once empirical models of the 1950's and 1960's demonstrated the usefulness of the concept, particularly with regard to economic efficiencies and applications to optimized water systems, researchers began to apply systematic approaches to understanding and utilizing conjunctive strategies. Maknoon and Burges (1978) used a table to show elements of conjunctive use and possible interactions between those same elements. The elements were "level of the problem, nature of the problem, physical, legal, and economic systems, objective(s), data, model of system dynamics, optimal policy, social criteria, and optimal policy implementation". A systematic analysis used a flow chart to demonstrate the unspecified water resources problems, uses of modeling, and implementing a selected optimal policy. Though the basic elements are discussed in the context of conjunctive use problems, the paper does not provide a detailed approach to defining a strategy for conjunctive management goals, criteria, or parameters for future conjunctive applications.

In the mid-1980's, a symposium of research dedicated to conjunctive use and irrigated agriculture resulted in a compilation of technical papers (World Bank 1998). The symposium included theoretical issues of economics and law, case studies from around the world, and reviews of various analytical methods. Rather than an overview of conjunctive use, the symposium researchers evaluated real-time applications of

conjunctive use and acknowledged concerns beyond modeling and optimal efficiencies. Thus, a comprehensive source of information about conjunctive use and its impacts on agriculture was made available through the symposium proceedings.

A workshop on conjunctive use water management in California evaluated 26 priority issues covering institutional, legal, stakeholder, financial, leadership, and water quality concerns (NWRI 1998). Invited experts evaluated the issues prior to meeting, and presented the results at the workshop. To expedite reviews of possible solutions to identified obstacles that prevent viable conjunctive use programs, experts evaluated possible solutions in advance and submitted their recommendations for workshop discussions and review. At the end of the workshop, participants ranked the 26 priorities. The top five priorities targeted institutional and legal obstacles between water agencies. Interestingly, in 2001 the California Department of Water Resources began a new conjunctive management program which emphasized partnerships, rather than state control, with local water agencies responsible for individual groundwater basins throughout the state (CDWR 2010).

In the late 1990's and around the beginning of this century, responses to growing drought conditions led to strong interest and research in conjunctive use as a possible water management tool for the Murray-Darling catchment basin of Australia. As part of ongoing research projects, a consulting firm developed a "decision framework" for the Murray-Darling Basin Commission (now the Murray-Darling Basin Water Authority) (REM 2004). The intent was to define an approach to guiding decisions about sustainable groundwater use. In doing so, the project team addressed the reality of conjunctive use interactions between surface water and groundwater. The framework

contained six phases – identification of resource management issues, quantification of water users and uses, confirmation of the decision environment, technical assessments, planning and implementation, and monitoring and evaluation. Each phase was divided into sub-phases to indicate the detail necessary to evaluate a potential program. While this technical paper has not been referenced by researchers and programs of the United States to a great degree, its similarities to a system analysis provide a foundation for better understanding conjunctive use program planning. As with the Maknoon and Burges' flowchart, a detailed analysis of moving through possible conjunctive project goals, primary elements and criteria, and a platform for usability regardless of location, was lacking in the Murray-Darling framework.

Review of the above efforts to formulate a general conjunctive water framework indicates that the results were, in general, only moderately successful. For example, the Maknoon and Burges flowchart addressed water resource issues, application of models, and implementation of optimal policy. The flowchart, however, is used in textbooks (Todd and Mays 2005) to demonstrate basic blocks of the conjunctive use concept. One indirect result of conjunctive use research and workshops was the state of California's modification of its conjunctive strategies to reflect partnerships between state and groundwater basins. Due to ongoing extreme drought stresses, water management research in the Murray-Darling Basin has expanded into the concepts and guidance of integrated water resource management. The Commission became the Murray-Darling Basin Authority as of December 2008, an agency enabled under Commonwealth legislation and binding agreement by all states reflecting the intensity of the multi-year drought and its heavy tolls on human society, economic conditions, and ecosystems.

These research and program efforts provide interesting examples of the evolution of conjunctive use but have limitations on the usability of the information or knowledge generated through the research. Water management decisions that include conjunctive strategies require more than a systems analysis or workshop proceedings. A new model and approach to understanding, consolidating data and information, and acting on conjunctive strategies are needed.

Conjunctive Strategy Platform

Evaluating the components that support viable conjunctive management – legal, economic, social, and physical water systems – indicate not only the strengths of conjunctive strategies but also the need to standardize a methodology for planning. As demonstrated through the results of a survey and interviews in the course of this research, water resource experts are familiar with the concept of conjunctive management, but persons involved in water resource research and management do not often agree on what conjunctive management is or how it might best be applied. In addition, while decision-makers, policy strategists, and water resource stakeholders may have heard of conjunctive use or management, they are less likely to be familiar with the technical and scientific disciplines underlying the concept. Water resource management programs of the past were largely decided by managers and technical experts within irrigation districts or municipalities. Within any one region, a small group of professionals made the majority of decisions regarding water. Currently, water management programs such as new dam and reservoir programs are accompanied by research and engineering studies, modeling, media stories, stakeholder forums, technical advisory groups, lawsuits, environmental assessments, economic evaluations, funding options, and overall a lengthy

decision-making process is the model of the future. Under such conditions it is imperative to inform decision-makers, policy strategists, and water resource stakeholders of water resource management options. Therefore, to fill a significant gap in developing and utilizing conjunctive management, this research proposes a “knowledge framework” to better understand and implement water management decisions made about conjunctive strategies.

This proposed conjunctive strategy framework is based on three key features: (1) the conceptual model encompasses the most basic elements of the framework; (2) the evaluated components are expanded to address current water resource issues; (3) a matrix of criteria and external factors are developed so as to build increased understanding of interactions between conjunctive components and site-specific characteristics and thus support decisions about conjunctive management options. The framework is designed to aid in applying conjunctive management as a long term, viable water management strategy. Its basis is the evaluations conducted in this research that allows a broader perspective and analysis than possible within the limits of any one research study or model.

Conceptual Model

A picture being worth many words, Figure 6.1 shows the visualization of conjunctive management as the core of elemental components. The diagram indicates the separate, but interrelated, nature of the components, and arrows denote flow of information. The top of the diagram indicates the regional water component extending into the surface water and groundwater systems. While the social, legal, and economic components do not physically extend into the water systems, there are relationships

between all the components through conjunctive management. The cylinders that form the components indicate the presence of data and information that are separate from the other components but connected through the program.

Closer to a physical concept, the conceptual model applied to a real world situation is shown in Figure 6.2. Flow arrows indicate movement in and out of the surface water and groundwater systems, similar to the well known hydrological cycle, though the large scale of the cycle is not shown. Detailed explanations and diagrams of the hydrologic cycle are found in the works of Todd and Mays (2005) and Dingman (2002). Figure 6.2 also focuses on the physical setting, as it is difficult to show qualitative components such as legal and institutional sub-components and interflow. Therefore, to understand relationships and flow of information between the separate components of conjunctive management, the concepts of the conceptual model are best visualized through Figures 6.1 and 6.2.

Components

In the conceptual model, the initial four components identified through previous research are expanded. One initial component, the physical water system, is replaced with three components – the regional water system, surface water, and groundwater. Ecosystems are also a new component in this model because within any region of water management, ecosystems and their active, living, ongoing processes provide observation points of the effects of water withdrawals and recharge, as well as being a primary water “user.” The economic component, with well researched and documented theory and programmatic applications in conjunctive use/management, includes financial information, thereby placing equal emphasis on the financial realities of water

management. The legal systems include institutions which uphold water law in daily life. The social/stakeholder component has been recognized in past research, but rarely takes on importance within the context of large scale water management. Here, the social/stakeholder component is of equal consideration along with the other components.

Together, the seven major components and related factors within a regional scale provide a solid foundation for improved understanding of the conjunctive management concept, the varied strategies possible through application of the concept, and what a conjunctive program may bring to a balance and sustainability of future water resources. The following definitions provide explanations of each component and its usage in the conceptual model.

- **Regional water system:** This is the area of water management bounded by the physical and geopolitical extent of water sources and uses. Overlain by political, geographic, and ecosystem boundaries, this component defines the extent of the area for conjunctive strategies as well encompassing the pertinent portions of surface water and groundwater systems.
- **Surface water:** This component comprises all inflows, outflows, storage, water uses, and infrastructure of surface water in the regional system. In many water management systems, surface water is the primary water source and therefore has decades of monitoring data, long-standing infrastructure, reliance of water users on quantity and quality and known financial management in place. There are established laws and institutional regulations on water use and societal and cultural expectations built on human interactions with water over generations.

Ecologic relationships with surface water are typically but not always better defined and understood than those with groundwater.

- **Groundwater:** Similar to the surface water component, a groundwater system comprises all inflows, outflows, storage, water uses, and infrastructure within the regional system. Groundwater can be a primary or secondary water source, or may physically exist within the regional system but currently not be part of water management. Data are dependent on well and spring records, and analysis or estimations of the groundwater structure and flow between well points. If available, groundwater maps and models often provide the best visualization of subsurface structures and water flow. If infrastructure such as well fields exist, then data are more likely to be accessible. However, in some cases the legal, institutional, and economic standings of groundwater, as well as the ecologic relationships and societal understanding of groundwater, are less defined due to fewer decades of groundwater studies and technology, as compared to those related to surface water. A key part of future conjunctive management is an improved understanding of inflows, outflows, and particularly storage factors involved in a groundwater system.
- **Ecosystems:** Although the structure and functions of ecosystems are reliant on the ebbs and flows of the water system, the interactions of human society with ecosystems have not always been considered in light of water management. This conceptual model brings forward the ecosystem component as equal in consideration to other components when deciding on water management strategies.

- **Economic/financial:** This component relies on understanding and utilizing the physical water system parameters. Economic studies build a relationship between the physical water system, its inflows and outflows, and relational economic data on how the water flows, use, and storage are quantified. The financial aspect brings real-time data to the economic studies. The cost of current and future strategies is critical to a societal agreement on how water management will take place and be funded over time.
- **Legal/institutional:** Of key importance to water users are their legal rights to water use, whether appropriative, beneficial, or part of a public trust. Chapter 4 reviews some variations and limits in water laws. While conjunctive use is not prohibited by law, it is also not equally supported in all cases. Therefore, water laws and existing institutions, qualitative rather than measurable in nature, can provide a framework of rules and limits in defining a successful conjunctive water management strategy.
- **Social/stakeholder:** Another qualitative component is the interactions and understanding of society in regard to water management. Where water is plentiful and flows from the tap, people are less likely to question future water sources, quality and quantity, and management strategies. In those regions that have experienced extended durations of water stress due to low flows, hydrologic or meteorological droughts, or degraded water quality, people tend to have a deeper appreciation of the water system, including the health of ecosystems, and are more likely to be involved in future water management decisions. This

conceptual model formalizes that relationship between people and water systems as the “social/stakeholder” component.

These seven components are the foundation to translating the conceptual model into a working framework for decision making. The conceptual model and its components are the basis of the framework, but require more attributes to become functional in application. A detailed approach is proposed in two levels, one that targets minimum criteria per component, and a second that shows the interactions between components and external factors. This approach supports an improved understanding of the physical water systems, available data and information within the conjunctive context, and evaluation of conjunctive management options by a water management planning team.

Criteria

Tables 6.1 and 6.2 list the information that is necessary, regardless of location, to formulate a conjunctive water management strategy. Analyzing this information in a systematic approach will help define the strengths and weaknesses of conjunctive options. Using readily available data and information is also part of a cost-effective planning effort. The gaps in basic data and information will open inquiries into what data will be needed to make a decision.

To clarify the conceptual model and define the basis of potential applications, Table 6.1 shows the fundamental criteria per component. These criteria are derived from analysis of physical water system programs and models, economic conjunctive models, legal frameworks, and surveys and interviews. The concept’s newly added regional system, financial status, and ecosystems are the result of overall conjunctive analysis of

gaps in the strategy as applied to established programs and also evaluated in the context of present-day and historic water management. The criteria require site-specific information for realistic design of a conjunctive program; however, the list of fundamental criteria is designed to provide water management teams a sound basis or starting point, as well as to support understanding of successful conjunctive management.

The components are separated under the general classifications of “Quantitative” and “Qualitative” (Tashakkori and Teddlie 1998). Quantitative components are identified by relevant, measurable, and usable forms of data, while qualitative information is recognized by its relative subjectivity. These two categories further define the conceptual model of integral components in viable conjunctive management.

Relevant questions at this point include the following: How are these criteria defined? What supports the list in Table 6.1, and what might be left out? A thorough evaluation of multiple conjunctive programs, research, and models under different disciplines supported the development of a new conceptual model and associated criteria for conjunctive management. The elements missing in previous research are an integrative approach for including in each program or model analysis the results of a previous evaluation. As elements such as inclusion of substantive ecosystems water needs into a study of water supply and water balance was lacking in many models, but identified in a few studies. A similar example is observed in the models that primarily focus on surface water; the groundwater component can be over-simplified through broad assumptions of groundwater inclusion in the model algorithms. In this research, such details are important to the overall success of a new conjunctive program. The conceptual model allows for variations in the overall balance of the components, but

requires consideration under the conjunctive strategy to be pursued. While the evaluations owe a debt to previous work in the field of conjunctive management, the model and criteria provide a new approach to conjunctive management strategies and decisions.

With the exception of general conjunctive management criteria, components in Table 6.1 are associated with site-specific criteria. For example, identification of conjunctive water sources under the “Regional Water System” component is possible only with site- or program-specific information. Available sources of water will be distinctly different for any region. Should more than one surface water source or more than one groundwater source be available, the identification will require evaluation of water characteristics, availability, existing infrastructure, and other information noted in the components.

Examination of Table 6.1, “Quantitative Components,” shows that each of the five quantitative, or measurable, components require data and information in order to provide a basis for understanding and implementing a conjunctive strategy. The regional water system component requires that optimal surface water and groundwater sources be identified. Are such sources available, or is the regional water system composed solely of surface water flows and storage? If the latter is true, an optimal conjunctive strategy involving the strengths in groundwater storage is not possible. For all three physical water components, identification and understanding of major characteristics existing infrastructure are necessary. Each criterion is structured to ensure that gaps as well as known data are recognized.

Table 6.2 addresses five criteria defined for general conjunctive management through additional descriptions, options, and examples. The criteria are fundamental to understanding what conjunctive management can offer for present and future water management. The first criterion, possible program goals, can be accomplished through implementation of techniques that are applicable to more than one goal, such as aquifer storage and recovery. While a technical program and operations may be similar, the design of the program to accomplish one or more specific goals is essential to its future success. The second criterion, taken from the data ranges (Chapter 2), re-emphasizes the broad potential of conjunctive management programs and geographic conditions.

The third and fourth criteria seek to underscore the degree of local and regional control and input. While state-led water management programs will continue to play a major role in water supply and implementation of federal interstate agreements, water management at a smaller scale is also desirable, and can be accomplished through conjunctive strategies which will not require an overhaul of existing water supply programs, but rather allow supplemental approaches. In addition, identifying and utilizing local data, information, research, water models, and economic analyses, is a key part of cost control in the decision-making process. Not only does such information have a lower cost, it also provides local support as conjunctive strategies are evaluated.

The fifth criterion of adaptive processes ensures that the program design will anticipate and react to changes in conditions. In the current world situation, no matter what the location or population, change in future water supply and demand must be anticipated in order for water management efforts to meet goals and be successful. Climate change and projected outcomes of modeled scenarios are only one type of

anticipated change. Other recognized and ongoing stress drivers on water management include population rate increases, establishment of large cities in regions of historic low water supplies, large-scale agricultural production whose water use has yet to significantly and sustainably decrease below an approximate range of 70 to 90 percent of water supplies, depending on location and irrigated crop yield and expectations, and the slow turnaround of urban centers to adopt water conservation measures. Taken together, or separately, these major issues require that near-future water management strategies be adaptable. One of the notable processes that has established procedures, protocols, and successful applications is adaptive management, a process through the life of a program by which monitoring and feedback loops provide information that is re-evaluated against previous data, models, and projected outcomes. The result can be a program with longevity, durability, and cost-effective measures incorporated in an ongoing basis.

Matrix of Conjunctive Components and External Factors

The third element of this proposed conjunctive strategy framework is a decision matrix (Table 6.3). The matrix builds on the components, expands fundamental criteria, and details the data, information, and parameters necessary to address major external factors of watershed, systems, infrastructure, water uses, and modeling and optimization. The process includes assessment of available data and developing the knowledge base with which to proceed with more costly water balance modeling. While assessing data and information, use of the matrix is envisaged for better definition of strengths and gaps in conjunctive strategies and options.

Assumptions for utilization of the matrix include: 1) a water management planning team has been formulated to address present and future water management and

is familiar with the region of interest, 2) a set of water management goals and desired water management targets are defined for the region, and 3) the minimum criteria are defined, answered, or separated into information gaps. The proposed matrix and overall framework work from another assumption, data integration and information building through each step. The matrix appears simple in nature, but is intended to ensure that each component of a conjunctive program is addressed. The results will provide a strong basis for improved understanding of conjunctive management, its strengths, and limitations, and decision-making about possible conjunctive management programs.

A brief overview of Table 6.3 follows. Each of the seven components of the conjunctive management conceptual model are linked with primary external factors identified as the program, watershed, physical water system, infrastructure, water uses, modeling and optimization, physical water and economic parameters, and unique economic parametric considerations. The links between components and external factors are the basic information and data required to address the relationships between components and external factors. The result is a rigorous approach for guiding decision-making, rather than a “roadmap” or a prioritized approach. As no element can be reliably ranked above or below another, ranking protocols are not included. However, the elements can be ordered and quantified within the decision process for specific goals and conjunctive programs. Due to the highly site-specific nature of conjunctive programs, the planning team is assumed to utilize the information and establish priorities based on project goals and realistic limits imposed by the regional system and conjunctive components. Thus, the framework supports an informed basis for decisions about

potential conjunctive management. This approach allows flexibility while providing a decision-building structure.

Finally, the conjunctive strategy framework – conceptual model, criteria, and decision matrix – are prepared with a team or task force in mind. The intent is utilization by a planning team formed within or associated with water user entities that are at a stage of inquiries into possible water management strategies that may work well for their regions. A team of experts and stakeholders can efficiently utilize the framework offered through the conjunctive tables and matrix, address the pros and cons of conjunctive management strategies, and make recommendations for follow-on stages of modeling, design, funding, and implementation of water management for the region. It is unlikely that experts in one field will also have the expertise to address the data, evaluation, and issues in other fields. However, a diverse planning team formed with the conjunctive components in mind will most likely have the required expertise, interested and informed stakeholders, and much of the necessary information accessible for evaluation. Therefore, the framework of conceptual model, conjunctive components, criteria and other relative factors is developed with such a team in mind, so that decisions about conjunctive strategies might be streamlined.

The framework is intended for use by planning teams. However, it is equally important to extract key information from the process of developing the framework and formalize how the components might enter into hydrologic studies of water flow. The following section describes inclusion of two elements, water conservation and environmental flows, that greatly informed the development of the conjunctive model and its potential applications in future water management.

Proposed Variables for Water Balance Calculations

One role that models perform in water management decisions is to provide quantitative expressions of the results of inputs, outputs, and changes in the water storage system. The basic algorithms for water balance, or water movement and storage resulting from inflow and outflow, demonstrate the foundational approach to water balance models. As explained in Dingman (2002), the basic water balance equation can be simplified to:

$$\text{for any period of time } (\Delta t), \Delta S = I - O, \quad (1)$$

where ΔS is change in storage, I represents all inflows to the system, and O represents all outflows. This equation is separated into major input and output variables:

$$\Delta S = (P + G_{in}) - (Q + ET + G_{out}), \quad (2)$$

where P is precipitation and G_{in} is groundwater inflow, together representing all inflows to the system. All outflows are represented by Q , or stream outflow, ET or evapotranspiration, including all evaporation from all surface water bodies and all transpiration from vegetation, and G_{out} , or groundwater outflow. Each variable is time-dependent, and depending on the period of time selected for analysis, some factors may be considered negligible. As well, each variable in equation (2) can be separated into more detailed factors, allowing better representation of the water system through measurable variables and constants. In model preparation, the most applicable models are those that address the problem under reasonable constraints.

The same is true of adding factors that support solutions of the water balance under varying conditions. In this research, the water balance references a conjunctive

system of water supply and demand. It is reasonable to include outflow factors such as water conservation and environmental flows that move through the system:

$$\Delta S = (P + G_{in} + C + EF_{in}) - (Q + ET + G_{out} - EF_{out}) \quad (3)$$

where the water balance inflows include EF_{in} , flows critical to ecologic systems and C , conservation measures, and outflows include downstream environmental flows, EF , expressed in units of flow.

The hydrologic research community at large may consider that conservation measures and environmental flows are sufficiently accounted through the established inflow and outflow variables in the water balance equation. The intent of this recommendation, however, is to register the need for targeted changes in water management at the base level of water balance calculations. If generally only considered and taught as a part of basic inflows and outflows, conservation and environmental measurements are more likely to be overlooked. The proposed changes to the basic water balance equation will aid in correcting such discounted needs in the water balance of physical water systems.

Conclusions

The purpose of the conjunctive decision-making framework is to clarify key parts of a practical and effective conjunctive management strategy, allowing the strengths and dependencies of the approach to be embodied in the data and information of any water system in a systematic evaluation that takes into account probable strengths and limitations of the approach. For this research, however, consideration of components and external factors in conjunctive management regardless of location or goal, ranking or ordering of components, factors, or parameters is not appropriate. Such evaluation can

only be conducted and verified within a specific region, compared against targets and considerations specific to that region. Also, creating a too-complex matrix and evaluation criteria does not necessarily aid in evaluating conjunctive management options. The complexity can fog the initial decision making process and is best reserved for a final round of modeled comparisons and cost analysis.

Use of the framework is intended for a planning team of water research experts, water management professionals, and stakeholders with basic knowledge of the overall water system. Working through the levels of information allows a basis for decision-making.

Chapter 7 takes into consideration the potential of conjunctive strategies in the Rio Grande basin and applied the conceptual model and criteria so as to explore the potential for conjunctive programs.

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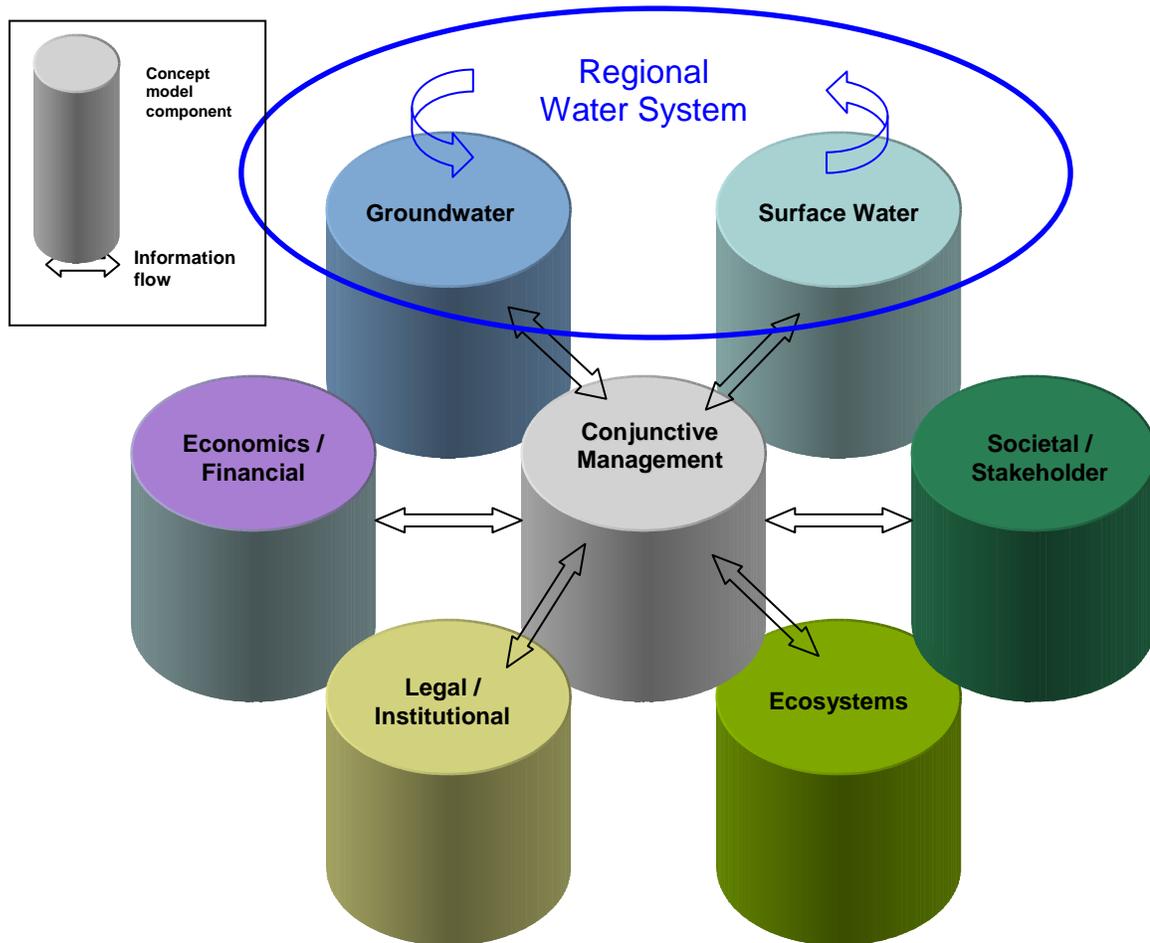


Figure 6.1 Conceptual Model

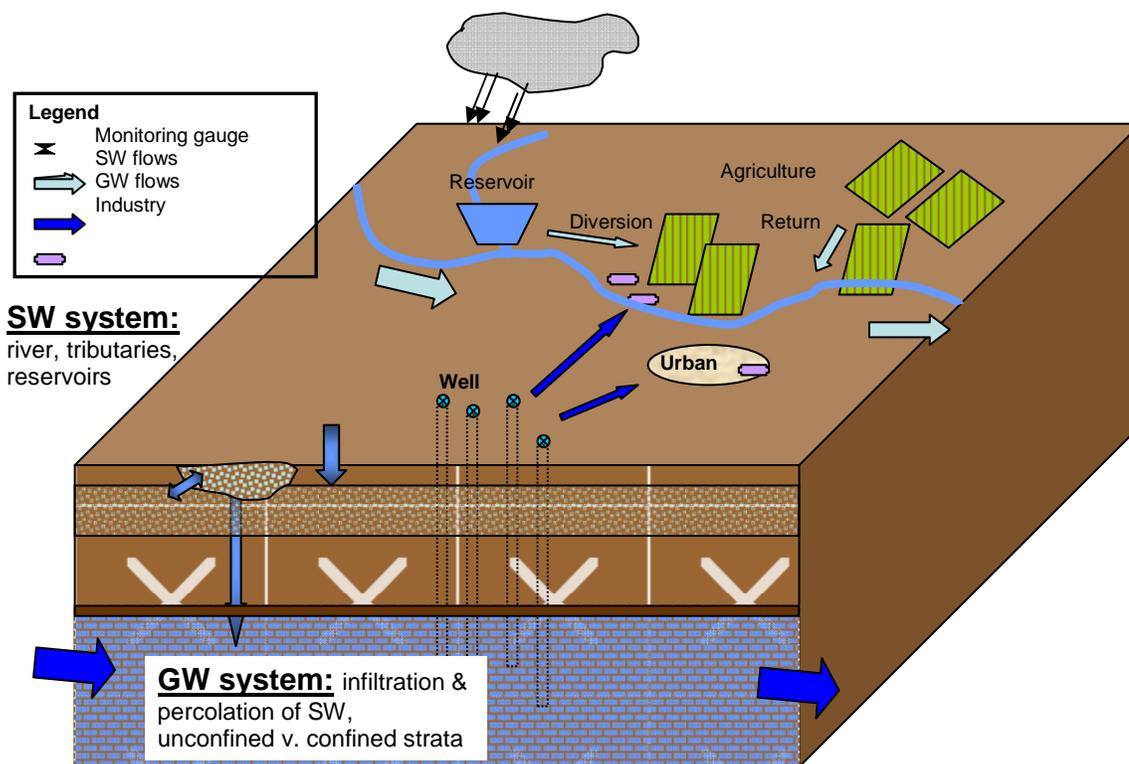


Figure 6.2 Physical Model

Table 6.1 Minimum Criteria

Components	Decision-Making Criteria
Conjunctive Management	<ol style="list-style-type: none"> 1. Program goal(s) will define level of effort (Table 6.2). 2. Specify boundaries of conjunctive program. 3. Identify options for local / regional control of program. 4. Identify and use available data and models to extent possible. 5. Build in adaptive processes.
Quantitative Components	
Regional Water System	<ul style="list-style-type: none"> <input type="checkbox"/> Identify optimal SW and GW sources with appropriate flow and storage characteristics. <input type="checkbox"/> Identify existing infrastructure and its components that may be available to a conjunctive program.
Surface Water (SW)	<ul style="list-style-type: none"> <input type="checkbox"/> Typically primary source of water supply with infrastructure. Identify major SW characteristics. <input type="checkbox"/> Degree of conjunctive management that can be developed into existing water supply program and infrastructure.
Groundwater (GW)	<ul style="list-style-type: none"> <input type="checkbox"/> Identify appropriate GW storage and retrieval characteristics of aquifer, and its extent. <input type="checkbox"/> Identify available groundwater/water supply infrastructure. Additional well and conveyance infrastructure may be needed.
Ecosystem	<ul style="list-style-type: none"> <input type="checkbox"/> Identify major ecosystems, biota, and habitats. <input type="checkbox"/> Build in ecosystem / habitat needs and environmental flows as water uses of the region.
Economic / Financial	<ul style="list-style-type: none"> <input type="checkbox"/> Identify cost/benefit analyses on water supply system, if available. Add information as necessary using available data <input type="checkbox"/> Analysis of historic and current water (SW & GW) prices, and tipping point of use between sources. <input type="checkbox"/> Identify funding options.
Qualitative Components	
Legal / Institutional	<ul style="list-style-type: none"> <input type="checkbox"/> Review established water rights & permits. Review legal framework to store and retrieve SW & GW. <input type="checkbox"/> Identify or create process for conflict resolution between water agencies and other water-related entities.
Societal / Stakeholders	<ul style="list-style-type: none"> <input type="checkbox"/> Identify water users with historically high usage rates; irrigated agriculture, urban (combination of municipal, industrial, other). <input type="checkbox"/> Identify projections of population or irrigated agriculture for specified timeline, with associated increases in water demands. <input type="checkbox"/> Participatory approach is utilized to understand and quantify the level of support for program.

Table 6.2 Detailed Criteria, Conjunctive Management Component

1. Goals
(a) Conjunctively Increase Water Supplies
<p>Example programs:</p> <ul style="list-style-type: none"> • Supplement low surface water supplies with pumped groundwater (Kern Co., CA; Canadian River Municipal Water Authority, TX) • Augment surface water flows through use of in-lieu, leased surface water rights banked with state agency to offset effects of groundwater pumping (CO water districts) • Recharge of permitted surface water to aquifer for drought mitigation storage (Bear Canyon pilot project, NM) • Aquifer storage and retrieval (ASR) (systems throughout western states and eastern seaboard; El Paso, Kerrville, and San Antonio, TX)
(b) Reduce Groundwater Overdraft
<p>Example programs:</p> <ul style="list-style-type: none"> • Artificially recharge GW using surface water or treated water supplies (Kern Co. and Santa Clara-Calleguas basin, CA; Central Arizona Project) • Aquifer storage and retrieval (ASR systems throughout CA basins; Kerrville, TX) (NAS 2008)
(c) Reduce Water Quality Degradation or Brackish Water Intrusion
<p>Example programs:</p> <ul style="list-style-type: none"> • Inject treated water into hydraulic barrier wells (Santa Clara-Calleguas basin, CA) • El Paso tertiary treatment system
(d) Support Environmental Habitat through Conjunctively Managed Systems
<p>Example programs:</p> <ul style="list-style-type: none"> • Supplement low surface flows with pumped groundwater to support salmon runs (model, Cosumnes River, CA)
2. General Boundaries
<ul style="list-style-type: none"> • Area of basin: 49 - > 8,000 km² • 1 + surface water system, 1+ groundwater system optimal • Surface water flows: no minimum or maximum, however, 0 flow rates must be temporary or seasonal, with high flows providing sufficient water to meet historic demands • Climate: arid to tropic conditions are possible • Precipitation: no minimum or maximum

Table 6.2 continued
3. Options for Local / Regional Control
<p>United States - state laws and regulations are typically dominant factor in water management funding and control.</p> <p>Other countries - federal water system predominate and not allow local control of water management</p> <p>Selected state-managed programs:</p> <ul style="list-style-type: none"> • CA: CALFED water management and transfers across state • AZ: Central AZ Project (CAP), which manages and stores water allowances of interstate river <p>Regional programs:</p> <ul style="list-style-type: none"> • CA: Kern County water bank • Far West TX / El Paso: ASR and conjunctive program developing under most recent water plan <p>Local programs:</p> <ul style="list-style-type: none"> • City of Kerrville: ASR through state well injection permit and utilization of surface water rights
4. Available Data & Models
<p>Identify existing water, economic, and ecosystems data and information through:</p> <ul style="list-style-type: none"> • Federal and state reports concerning the watershed and aquifers • State and county water, soil, and groundwater databases • Local water utility databases • Local academic research and reports <p>Identify existing water balance and economic / water resource models:</p> <ul style="list-style-type: none"> • State or regional water models • Models reported to state agencies as part of other research • Local academic models
5. Adaptive Processes
<p>Utilize protocols of existing adaptive management programs:</p> <ul style="list-style-type: none"> • Example – Florida Everglades program of multiple projects and issues

Table 6.3 Conjunctive Strategy Planning Matrix

Primary Factors and Required Information per Component							
	<i>Quantitative</i>					<i>Qualitative</i>	
<i>Component:</i> Factor:	<i>Regional Water System</i>	<i>Surface Water (SW)</i>	<i>Groundwater (GW)</i>	<i>Ecosystems</i>	<i>Economic/Financial</i>	<i>Legal/Institutional</i>	<i>Societal/Stakeholder</i>
Program	Projected targets & outcomes of conjunctive mgt program	Targeted SW source(s); impacts on existing SW system	Targeted aquifer & impacts on system	Targeted benefits & possible ecological impacts	Targeted benefits & expected costs; funding sources	Legal & water agency support & limits at state, regional level; similar programs	Use of existing forums, workshops to determine public support for conjunctive program
Watershed	General watershed, land, climate characteristics	Estimate SW available for program goal	Estimate GW available for program goal	Ecosystem(s) in watershed; endangered & threatened species; current mitigation actions	Socio-economic data for region; funding mechanisms for existing water supply	Established water & property rights	Stakeholder water needs, concerns
Physical Water Systems	SW, GW water supply sources, characteristics, water quality, SW/GW interactions	Available data on stream, rainfall, runoff, reservoir characteristics	Available data & characteristic factors about aquifer & confining layer (if any)	Potential impacts of conjunctive management on ecosystems; capacity of program to join current mitigation actions	Use available data for cost/benefit analysis of conjunctive program & alternatives	State rules & water district rules (if any) for SW & GW under conjunctive approach	Water user groups – demographics, specific water uses, projected supply & demand

Table 6.3 continued

Component: Factor:	Regional Water System	Surface Water (SW)	Groundwater (GW)	Ecosystems	Economic/ Financial	Legal/ Institutional	Societal/ Stakeholder
Infrastructure	Infrastructure: existing; potential for additional infrastructure; current water treatment standards & capacity	Potential for additional infrastructure; facilities for artificial GW recharge, if applicable	Determine existing infrastructure for GW extraction	Potential impacts to riparian & spring habitats, & possible support for current mitigation actions	Funds for current O&M; potential funding for conjunctive facility improvements	Permits required for additional infrastructure, if needed	Determine how much of existing water supply infrastructure, model(s), economic valuations can be used to reduce costs
Water Uses	Existing & future water uses by category (agriculture, urban, etc.)	Specify existing SW uses, volumes of inflows & outflows	Specify existing GW uses & status of aquifer levels during times of peak & low usage	Determine SW & GW use impacts of existing water supply on ecosystems	Determine potential for water markets to support lowest SW & GW prices	Determine legal framework for water markets	Compare projected supply & demand to that under proposed conjunctive program
Modeling and Optimization	Utilize existing water balance model(s); develop scenarios for outcomes & tradeoffs; establish optimal & beneficial uses	Inputs to water balance model; estimate potential & desired outcomes for SW source(s)	Inputs to water balance model; estimate potential & desired outcomes for GW source(s)	Estimate environmental flow target(s) for inclusion in water balance	Economic inputs to model through marginal costs, revenues; evaluate water balance & optimal scenarios against cost/benefit analysis	Outflows to include any treaty/compact/other downstream flow requirements	Estimate water conservation target(s) for inclusion in water balance model

Table 6.3 continued

Component: Factor:	Regional Water System	Surface Water (SW)	Groundwater (GW)	Ecosystems	Economic/ Financial	Legal/ Institutional	Societal/ Stakeholder
Major Physical Water System Parameters	<ul style="list-style-type: none"> - Flows, highs & lows, throughout system - Reservoir storage; schedule of storage & releases - System-wide return flows to SW - SW & GW interconnections 	<ul style="list-style-type: none"> - Upstream & downstream flows; changes over time - Infiltration, percolation, evapotranspiration rates - Reservoir characteristics over time - SW (streams, tributaries, lakes) characteristics over time - Base flow to/from GW (gaining or losing stream segments over time) 	<ul style="list-style-type: none"> - Aquifer characteristics, geology, storage pros & cons for conjunctive strategies - Recharge & discharge; changes over time - SW flows to/from GW - Pumping rates over time - Water table evaporation 	<p>Water uses:</p> <ul style="list-style-type: none"> - Maintain ecosystems & habitats through times of water stress 	<p>Benefits:</p> <ul style="list-style-type: none"> - Water use - Revenue from water use (agriculture, hydropower, urban, industry, mining, rural, ecological uses) - Incentives: taxes, subsidies, water market benefits & tradeoffs <p>Costs:</p> <ul style="list-style-type: none"> - Impacts of withdrawn water - SW & GW infrastructure, improvements, operations, maintenance - Irrigation efficiency improvements - Water treatment 	<ul style="list-style-type: none"> - Regulatory controls on SW, GW, ecosystems - Treaty/compact requirements - Environmental flow requirements - Water conservation rules & measures 	<p>Water uses:</p> <ul style="list-style-type: none"> - Water supply (urban, agriculture, industry, etc.) - Irrigation - Fish hatchery - Parks, nature preserves - Recreation - Reservoir site

Table 6.3 continued

Component: Factor:	<i>Regional Water System</i>	<i>Surface Water (SW)</i>	<i>Groundwater (GW)</i>	<i>Ecosystems</i>	<i>Economic/ Financial</i>	<i>Legal/ Institutional</i>	<i>Societal/ Stakeholder</i>
Major Economic Parameters	<ul style="list-style-type: none"> - Cost/benefit for conjunctive mgt options in region - Costs to use existing infrastructure - Funding, operations, annualized additions to infrastructure 	<ul style="list-style-type: none"> - Revenues (crop yield, urban fees, etc.) or valuation of SW use - Marginal SW costs - Conveyance costs - As applicable, agriculture drainage costs (irrigated soils & salinity issues) 	<ul style="list-style-type: none"> - Revenues (crop yield, urban fees, etc.) or valuation of GW use - Marginal GW costs - Well installation costs - Pumping & energy costs - Conveyance costs - As applicable, aquifer storage & recovery costs 	<ul style="list-style-type: none"> - Valuation of relative conjunctive mgt impacts on ecosystems - Valuation of alternative water mgt approaches & impacts on ecosystems - Costs of potential mitigation measures due to conjunctive program 	<ul style="list-style-type: none"> - Design, modeling, implementation, & operational costs of targeted conjunctive program 	<ul style="list-style-type: none"> - Legal & permit fees - Costs of compliance with water agency rules 	<ul style="list-style-type: none"> - Perceived socio-economic benefits & costs of conjunctive program vs. alternative programs

Table 6.3 continued

Component: Factor:	Regional Water System	Surface Water (SW)	Groundwater (GW)	Ecosystems	Economic/ Financial	Legal/ Institutional	Societal/ Stakeholder
Unique Economic Parametric Considerations	- SW scarcity value linked to upstream GW pumping or changes in storage		- GW levels as valuation of social welfare - GW valuation as buffer - Costs of GW use by individuals vs. central agency		- Water market options	- Marginal willingness to pay within tiered rate structure	- Well capacity as estimated of risk aversion in SW vs. GW use decisions - Marginal willingness to pay within tiered rate structure

CHAPTER 7

CONJUNCTIVE MANAGEMENT IN THE RIO GRANDE BASIN

Issues of Conjunctive Management

The Rio Grande/Rio Bravo del Norte basin (Rio Grande) has experienced unprecedented stresses on its water resources. Whether one considers the effects of drought, occasional extreme floods, or water quality degradation, very few places along the river might be defined as pristine. Several times in 2001, the river ceased to flow to the Gulf of Mexico for several months at a time, a great concern to humans and a threat to estuarine and marine environments (Sansom 2008). In addition, growing population centers along the river require increasing quantities of clean, safe, and usable water, despite increased conservation methods that have helped decrease per capita use in recent years. (Such decreases are exemplified in El Paso, Texas, where active water conservation has reduced per capita water use to 139 gallons per day per person in 2003; Environmental Defense Fund 2008). To address current and future water solutions, practical ideas and in-depth discussions about increasing water management efficiency warrant serious consideration by water agencies and basin stakeholders.

One water management approach with the flexibility to address multiple aspects of these water stresses and challenges is conjunctive use, also known as conjunctive management. Simply stated, it is the optimized use of water sources over time when more than one water source is available. In theory, it is straightforward to use one or

more water sources, or to utilize one source while another source is conserved, stored, or allowed to recharge. In reality, the conjunctive approach may be difficult to implement as a practice, particularly when other water management tools have been in place for years, particularly those approaches that rely on existing infrastructure and accessible surface water supplies. Over the decades since recognition of conjunctive use for water management, it has been recommended in numerous research and policy documents. Definitive methods for development or implementation, however, are rarely included in such documents. Such a gap indicates a lack of knowledge and/or agreement on which scientific, economic, and political factors determine whether conjunctive management is a viable water management strategy. A new approach is needed to integrate the concepts, major components, and a framework with which to understand conjunctive strategies, goals, and applicability.

This research focuses on selected regions in the Rio Grande basin, with the potential for conjunctive strategies to assist in reaching water management goals. The next section provides an overview of the basin and relevant systems, as well as an overview of conjunctive programs currently found in the basin. A methodology for addressing essential conjunctive criteria is the topic of the third sections, followed by selected regions for application of the methodology. Conclusions and recommendations for addressing conjunctive management as a site-specific strategy are included in the final section.

Physical Setting and Existing Conjunctive Programs

Watershed and Hydrology

With a drainage area of approximately 472,000 km² and a length of 3,033 km, the Rio Grande is among the 25 longest rivers in the world. It flows from the southern Rocky Mountains of Colorado, south through central New Mexico, and then south and east between Texas and Mexico, to drain into the Gulf of Mexico. The river receives drainage from two countries, three U.S. states, five Mexican states, and more than 20 Native American nations. Major tributaries are the Rio Conchos, which supplies the majority of mainstem surface water in the Presidio/Ojinaga area, and the Pecos River, which joins the river to flow into International Lake Amistad. The Río Conchos has a drainage area of 68,375 km², including three large tributaries, Río Chuviscar, Río San Pedro, and Río Florido (IBWC 2002).

With the exceptions of mountainous headwaters, its route through high elevation grasslands in northern New Mexico, and the productive bays and estuaries near the Gulf, the Rio Grande is primarily a river of the desert. Its character is demonstrated as much by limited flows, seasonally and spatially, as by extreme high and low flow conditions. Several reaches, such as the Forgotten River between El Paso and Fort Quitman, segments within Big Bend National Park, and the rivermouth at the Gulf of Mexico, ceased to flow over the last decade due to drought and other factors (Sansom 2008).

Springs

Hundreds of springs are found in the watershed, including Hot Springs near the Elephant Butte Reservoir, at least 13 major springs near the river in Coahuila (Boghici 2004), San Felipe Springs in Val Verde County, Texas, and the Las Moras/Pinto Springs

system in Kinney County, Texas. The springs typically respond quickly to rainfall; historic flows in the Texas springs range from a low of 0 cubic meters per second (m^3/s), to an estimated $4.22 \text{ m}^3/\text{s}$ in the San Felipe Springs in 1899 (Brune 1975). Spring-fed rivers, such as Las Moras Creek and Devils River, provide significant flows to the Rio Grande downstream of Amistad Reservoir.

Aquifers

A significant component of the basin's water resources is groundwater (Robson and Banta 1995). These subterranean waters interact with rivers, support habitats, and are of great importance to the watershed's hydrologic system. Acting as storage reservoirs, shallow groundwater provides baseflow to the river in some areas, while the river provides recharge to groundwater in other locations. Without groundwater discharge, springs along the river and adjacent lands would cease to flow. Much of the river flow downstream of the International Amistad Reservoir is from springs and spring-fed streams on both sides of the border (Boghici 2004). If groundwater supplying these springs should be negatively impacted, significant inflow to the river would be reduced.

Aquifers are found along the length of the Rio Grande. East of the headwaters in the southern Rocky Mountains of Colorado are the San Luis Valley aquifer systems. These systems were formed by tectonic rifting that began around 26 million years ago (mya) and continues to the present day. The aquifers extend into northern New Mexico (Wilkins 1998). Known as "basin-fill aquifers", they are bordered to the east and west by normal faults, with up to 20,000 feet of vertical displacement (Robson and Banta 1995). Discontinuous geologic bounding has allowed development of open and closed basins

along the Rio Grande valley. The closed basins have no surface water drainage, therefore tending to contain waters with much higher salinities than for the open basins.

The aquifers can be very productive. Agriculture in the San Luis Valley of southern Colorado depends on a recharge of 101 m³/s. This recharge rate is about 15 times the recharge of the next largest basin in the upper Rio Grande region (Wilkins 1998). Around Albuquerque, however, “induced recharge” may be a significant water source. This type of flow is caused by groundwater levels near rivers being impacted by excessive groundwater pumping. The low groundwater levels can induce a “losing stream,” whereby some of the subsurface waters flow into the aquifer. Estimates of induced recharge around Albuquerque indicated that 80% of the pumped groundwater was induced between 1920 and 1960 (Robson and Banta 1995).

Demographics

Large agriculture regions predominate in the San Luis Valley, the region around El Paso and Ciudad Juárez, and the lower Rio Grande Valley. Agriculture is by far the largest water use in the basin. Of the 2010 projections for water use in the El Paso and surrounding counties, 175,540 of the total (193,171 acre feet), or around 91 percent, will be needed for irrigation (TWDB 2007). Industries and municipalities are associated with 14 bi-national “sister” cities located along the Rio Grande. Municipal population growth is a major factor in calculating future water demands upon the river. Whereas population growth on each side of the border was estimated to be 26 percent during 1980–1990 (TWDB 2002), growth in El Paso and surrounding counties is projected to increase by 79 percent between 2010 and 2060 (TWDB 2007). Corresponding water demands projected

for 2060 in the same region indicate a 9 percent increase in agricultural water use, but a 51 percent increase for municipal water demands.

Legal Framework for Water Resources

The U.S. states of Colorado, New Mexico, and Texas have relatively similar approaches to water law and individual water rights. In western U.S. water law, prior appropriation recognizes property rights, allocation through permitting, and senior vs. junior water rights. Beneficial use of the permitted water is another common theme. Colorado uses prior appropriation and adjudication for surface water permitting; groundwater is managed through permits and local groundwater districts (Hobbs 1997). Through the State Engineer's Office, New Mexico manages surface water through prior appropriation, and groundwater is managed within specific districts and well permits. Texas utilizes prior appropriation and water rights for surface water. However, groundwater is either managed through groundwater conservation districts or by rule of capture in non-district areas (see Chapter 4 for discussion of groundwater districts in Texas).

The 1917 Constitution of México establishes federal domain over land, mineral resources, and water bodies, with the exception of a 2001 amendment that recognizes the rights of indigenous communities to natural resources. Thus, water statutes are founded on the Constitution, including water utilization prioritization, federal jurisdiction for all water delivery systems, and restricted zones and a permitting system for use and development of groundwater (Hernandez 2003). In addition, Article 27, Section 5, of the Constitution allows landowners to appropriate underground waters. If the public interest is affected, a "concession" is required under an extensive program, created to permit and

manage these concessions. The 1992 National Waters Law created a new government agency, the Comisión Nacional del Agua (CNA), vested with all federal authority regarding national waters. The law also obligates all water users to pay fees for the use of national waters.

Certain uses may be permitted, including public urban use, agricultural use, power generation, and other productive functions. These uses apply to groundwater as well as surface water.

In the Treaty of 1944, the International Boundary and Water Commission, a bilateral agency, was created to handle water issues along this border, (IBWC 1944). The IBWC's primary focus is on surface water allocations and associated issues. In response to the North American Free Trade Agreement of 1992, the Border Environmental Cooperation Commission (BECC) was created to review groundwater and surface water problems associated with contamination along the U.S.-Canadian border and the U.S.-México border. The North American Development Bank (NADBank) finances projects to address pollution and other related problems along the borders.

In summary, the hydrologic system of the Rio Grande watershed is an intricate system of surface water bodies and aquifers, as well as a complex array of natural habitats and human infrastructure. Droughts and floods affect the inhabitants, as does pollution. The laws that provide the framework for managing water also greatly vary, posing barriers to integrated water management within the basin. The challenge is to develop appropriate approaches, boundaries, and limits for potential conjunctive management in the basin.

Overview of Three Conjunctive Programs

Within the Rio Grande basin and chiefly near the river's mainstem, three conjunctive water programs demonstrate the strengths of the water management approach. The first, the San Luis Valley in southern Colorado, indicates how conjunctive use can move from issues involving interactions of surface water and groundwater into the state's legal system. The second is an innovative demonstration project near Albuquerque, New Mexico, concerning storage of surface water through artificial recharge and legal precedents for similar projects. Lastly, the Far West Texas planning region, one of 16 such regions in Texas, and the city of El Paso have included conjunctive management and aquifer storage and recovery as part of their long-term strategies for maintaining water availability through low flows and drought. A map of the basin and pertinent conjunctive management regions is shown in Figure 7.1.

San Luis Valley, Colorado

As true of most western U.S. states, evolution of water law in Colorado over the last 150 years can be traced to its history, settler expansion, scarce water supplies and disputes in times of drought, and understanding how surface water systems are linked to aquifers. The resulting Colorado system of water law is complex, multi-layered by intention, and has evolved over the years to deal with previously unknown water issues. Though the majority of laws deal only peripherally with conjunctive use, several legal milestones set precedent for conjunctive water management in Colorado.

During the early 1900's, state law embraced prior appropriation, beneficial use, and the right to transport or deliver water to lands not immediately adjacent to streams or tributaries (Hobbs 1997). Groundwater in Colorado was not well regulated, but was

increasingly used for irrigation in the valley and other agricultural areas of the state. Unexpected changes in stream levels led to the supposition that increases in pumping wells affected stream flows. In the 1960's, hydrologic studies determined that such was the situation. The 1965 Groundwater Management Act was intended to bring groundwater into surface water rule. Along with designation and management of local groundwater districts, the Act authorized the State Engineer to protect surface water rights by managing well permits, including denial of permits on the basis that pumped groundwater could affect diversion of surface water. This Act, along with existing surface water law, was intended to provide full economic development of water rights and bring into effect the conjunctive administration of surface and groundwater. Furthermore, the 1969 Water Determination Right and Administration Act created a system of water districts and adjudication procedures for water rights to surface and tributary groundwater. Well pumping came under the existing priority system, but junior rights would not be curtailed unless they caused definable injury to senior water rights.

In addition to the growing metropolis of Denver, several agricultural regions of Colorado have experienced myriad water issues and lawsuits over the years. The San Luis valley, located near the headwaters of the Rio Grande, is a small region with a fairly short growing season due to its elevation, but one remarkable for its famous river and the large volume of groundwater, located in shallow, unconfined water tables and artesian aquifers. The Rio Grande runs through the valley, and the productivity of irrigated lands using surface and ground water has remained high for decades. Crops include hay, alfalfa hay, spring wheat, spring barley, fall potatoes, spinach, lettuce, and carrots (SLVRC 2009).

While the lawsuits that have brought the South Platte and Arkansas River regions to national attention have not been as prevalent in the San Luis Valley, the groundwater is tributary to the river in the valley and therefore subject to concerns under low flow and low rainfall conditions. Conjunctive use in the valley is seen as necessary for productive and economically viable lands, while being subject to changes in state laws. The interstate compacts concerning Rio Grande flows from Colorado into New Mexico and Texas also play a part in managing the water system. The valley provides an example of a conjunctive use system that is not formally managed as a project to achieve specific goals, but rather, a system that evolved out of local and state water needs, responses of the legal system to resolve conflicts, and ever-changing water rights, water demands, and fluctuating water supplies.

Bear Canyon Recharge Demonstration Project, New Mexico

Water resources in New Mexico are subject to prior appropriation and beneficial use. The appropriation system is one of senior and junior rights, overseen by the Office of the State Engineer, and beneficial use provides a measure by which to use waters of the state under permit (Lieuwen 1997). Administration of surface and ground water rights are conjunctive, with the intended effect of protecting surface waters from depletion due to groundwater withdrawals, and ensuring that water deliveries are made as required by interstate compacts. In effect, the groundwater storage potential of conjunctive management is considered limited due to the rights tied to surface water.

A unique artificial recharge demonstration project is underway in the Albuquerque area (Moore et al. 2007). While artificial recharge projects exist throughout the western states, to date there are no other operating and permitted projects in New

Mexico. The Bear Canyon project has been designed to demonstrate that artificial recharge can effectively provide recharge to an aquifer hydraulically connected to a stream system. The project utilizes surface water rights to San Juan-Chama river flows. The allocated water is used to recharge the regional aquifer through an infiltration system in the stream into the shallow aquifer. Monitoring of the system provides data and information on infiltration rates, water quality, and other parameters that will characterize the aquifer's storage potential. Project goals include use of surface water to recharge the aquifer, monitor water quantity and quality stored, and to establish a legal right to the stored water (Moore et al. 2007). This project, one with strong conjunctive use factors, may provide a precedent of permitted, stored, and retrievable surface water in an aquifer. In the New Mexico water system, already conjunctively managed in its administration oversight of surface and ground waters, the project may demonstrate the applicability of conjunctive use within a definite geographical location and time frame.

Strategies in the Far West Texas Water Planning Region

To better understand the water needs of different geographic areas around Texas, the 1997 Senate Bill of the 75th Texas Legislature created regional water planning groups (RWPGs) (TWDB 2007). The regions and boundaries were developed based on geographic location of river basins, aquifers, socio-economic factors, municipalities, climatic zones, and other considerations, resulting in 16 RWPGs across the state. During each 5-year planning period, the RWPGs are required to evaluate current and future population growth and associated water supplies and demand. Should the projected supplies not meet future demands and uses, the groups must assess strategies to meet the region's needs. One such strategy is conjunctive use.

The Far West Texas Water Planning Group (FWTWPG) is the RWPG responsible for coordination of water resource planning in El Paso County and six counties to the east and south. The 2002-2007 regional plan highlights the population growth centered on El Paso, projected to increase around 79 percent by 2060, and a corresponding future increase in municipal water demand by 51 percent. However, agricultural water demand, by volume the highest use, is projected to decrease 9 percent during the same time frame (TWDB 2007). Total water demands for the next 50 years may exceed available supplies. In addition to strategies to meet agricultural and other water needs in the entire region, the RWPG has recommended a set of integrated strategies to meet water needs in El Paso: conservation, reuse, conjunctive use of Rio Grande and groundwater, and evaluation of additional groundwater supplies (FWTWPG 2006).

Based on current conjunctive use by the El Paso Water Utilities (EPWU), the long-term strategy of conjunctive use relies on pumped groundwater from local aquifers to supplement or replace low flow surface water availability during winters and times of drought. The basis for surface water use is El Paso's ownership and lease rights to use Rio Grande waters; if all agreements are met during a year, El Paso has rights to 65,000 acre-feet (FWTWPG 2006). Under the conjunctive use strategy, leases and rights to groundwater would bring in 10,000 to 20,000 acre-feet per year of pumped groundwater into the Far West regional water resources system. Projected capital costs for this conjunctive use are \$103M, including an additional 20-acre treatment plant, and operations and maintenance costs are estimated to be \$13M over 30 years and \$5.6M over 20 years (FWTWPG 2006). Assessed impacts suggest that the increase in pumped groundwater, up to 20,000 acre-feet per year, would not significantly impact groundwater

quality. The conjunctive use strategy is one of six components in the Far West Texas Region future water supply. Water supply realized from conservation, reuse, and purchases and leases to other groundwater sources are equally critical to long term success.

The FWTWPG recommendations are reflected in the El Paso Water Utilities' "10-Year Strategic Plan" (EPWU 2009). Under the goal for "Government Affairs, Communications, and Marketing Initiatives," Goal II-D, the Board states that it will work with state and federal entities to "promote and implement the utility's state and federal agendas." One measurement of this goal is "continuing to emphasize the need for water resource flexibility through the combination of desalination, importation, surface water purchases, and land acquisition for groundwater rights in order to provide varied approaches in maintaining a sustainable water supply." This goal is further developed in the document's Resource Management Initiative, Goal III-K, acquisition of new water rights "to ensure availability of water resources, especially during times of drought." One of the measurements is integrated water management strategies, under which the conjunctive use of water is included.

In addition to the planned conjunctive strategies, El Paso operates a managed aquifer recharge system (also identified by Sheng (2003) as an aquifer storage and recovery system in use since 1985). The system utilizes reclaimed wastewater from the El Paso Water Utility system, stores the treated waters in the Hueco Bolson aquifer, and recovers the water for use from downgradient production wells. The system has recharged over 75 million cubic meters since its inception.

El Paso provides an example of how conjunctive use may be evolving in the Rio Grande basin. Rather than implementing one large-scale, “fits-all” strategy, the planning groups and stakeholders are working with multiple approaches that provide integration between existing infrastructure, water resources, funding options, and feasible strategies to meet future needs.

In conclusion, the existing conjunctive programs and strategies discussed above provide succinct examples of the applicability of conjunctive management in other locations. Each program operates under distinct legal frameworks, socio-economic conditions, and physical water settings. Under the auspices of the Colorado water district system of stream augmentation to maintain senior water rights and junior pumping rights, the San Luis valley maintains high agricultural productivity through application of Rio Grande and groundwater throughout the growing season. The Bear Canyon demonstration project is a forerunner for permitting recharge, storage, and future withdrawals of stored surface water. The Far West Planning Region around El Paso is in the process of implementing various water management strategies to more efficiently use and store water for future needs. While each program exhibits advantages and various considerations, it is clear that no one program demonstrates all possible strengths of conjunctive management. The following section addresses utilization of a framework that considers major factors of conjunctive strategies and applies that framework in the Rio Grande basin.

A Platform for Conjunctive Management Decision-Making

The three conjunctive programs demonstrate the effectiveness of conjunctive strategies as well as the site-specific nature of each program. What works well in one

region, such as augmented stream flows to compensate for groundwater pumping depletion of stream flows in the Colorado water districts, may not work well in other regions. What potential exists for future application of conjunctive strategies in the Rio Grande Basin?

First, the three conjunctive water programs reviewed above clearly indicate the ongoing water stresses and future water demands in the Rio Grande basin. As well, certain types of regions stand out in water planning that are adaptable to conjunctive strategies:

- Waters-stressed regions, particularly around municipalities and agricultural production in semi-arid to arid conditions
- Movement of water from agriculture to city uses via permit transfers and water leases
- Aquifers that are experiencing overdraft conditions
- Growing population centers

Water management goals that have been noted in research and state water planning and are of interest in the basin include:

- Increasing water supplies and water system reliability
- Storing surface water that may not be used at the present time but is estimated to be needed during future droughts
- Decreasing groundwater overdraft
- Determining management alternatives that are cheaper than new surface water reservoirs

As described in Chapter 6, the conjunctive management decision framework presented in this dissertation was prepared to develop data, information, and knowledge concerning potential conjunctive strategies. The goal is to support decisions concerning conjunctive management decisions in such a manner that the strengths and weaknesses of a proposed program will be clarified and the ultimate decision well-founded. Using the Lower Rio Grande Valley as an example, the following section describes how the framework can be applied and the results with regard to potential conjunctive strategies. Furthermore, as the international border between Texas and Mexico is part of the valley, potential transboundary conjunctive approaches are discussed along with their possibilities and limitations.

Conjunctive Management Potential in the Lower Rio Grande Valley

Figure 7.1 is a map of the watershed that includes locations of major conjunctive water projects. The Bear Canyon project discussed in the above section is shown as the same general conjunctive location as that of Albuquerque, New Mexico. Four regions that may potentially benefit from implementation of conjunctive strategies are hatch-marked on the map. These regions include the city of Santa Fe, New Mexico; the agricultural and urban communities from Las Cruces, New Mexico, south to El Paso, Texas, and Ciudad Juarez, Chihuahua, in Mexico; the region around Presidio, Texas; and the lower Rio Grande valley extending from McAllen to Brownsville, Texas, and Matamoros, Tamaulipas, in Mexico.

These regions highlight some of the water stress concerns and potential conjunctive management goals in the basin as listed in the preceding section. Santa Fe (NM) is an example of an urban center in the basin with strict development policies and

water conservation measures in place. Due to low surface water flows in the region, a high degree of interconnectivity between surface water and groundwater, and limits on well pumping in the state-designated water basin, water concerns are consistently a part of the public dialogue in development policies. Similarly, the isolated region about Presidio (TX) uses permitted river water and groundwater from the Presidio Bolson primarily for municipal, agriculture, and ranching uses. Both Santa Fe and Presidio could likely benefit from consideration of artificial recharge similar to the Bear Canyon project or an aquifer storage and recovery (ASR) system.

The region around Las Cruces, El Paso and Ciudad Juarez highlights the need for consideration of transboundary conjunctive management. While the El Paso municipality and its water utility have moved from planning to implementation of conjunctive water strategies that provide alternatives to reliance on the Rio Grande waters, the other two municipalities have water management in place that continues to rely on separate programs of surface water use and groundwater pumping. The opportunities and limitations of transboundary conjunctive management are discussed in the next section.

The lower Rio Grande valley, transboundary in nature between Texas and Mexico, extends south of Falcon Reservoir along the river to the Gulf of Mexico. On both sides of the border, productive soils and fairly constant water supplies support high agricultural growth. Urban centers have also seen a high growth rate and increased socio-economic conditions. The lower Rio Grande Valley is part of Region M, one of 16 state-based water planning groups in Texas. Region M has noted interest in conjunctive strategies to help sustain water supplies but has not identified explicit goals, target areas, or specific conjunctive approaches (Region M Water Plan 2006). In recent water plan

drafts, Region M strongly indicated water supply concerns from the transition of agricultural to urban water uses (Region M Water Plan draft 2010). These issues and related factors discussed below support strong consideration of conjunctive strategies.

As discussed in Chapter 6, the framework for generating sound decisions about conjunctive management is based on a model of components, criteria identified through evaluation of conjunctive programs and research, and a decision-making matrix.

Application to a specific region requires a planning team such as exists within the Region M Regional Water Planning Group (RWPG), knowledge of the area and water supply issues such as demonstrated in the Region M Water plans 2006 and 2010, and identification of conjunctive management as a potential strategy for the region. These conditions exist in Region M as well as many of the 16 water planning regions in Texas.

For expediency and keeping costs of planning low, conjunctive strategy evaluations are best begun with available data and models. Through the state water planning process, all 16 water planning regions have collated available data and have various water models available through research studies. In addition, two major models have been prepared and utilized at the state level. Managed by the Texas Commission on Environmental Quality, the Water Availability Model (WAM) handles current surface water rights and allocations for all of Texas' watersheds. Generated for major and minor aquifers in Texas, the Groundwater Availability Models (GAMs) are managed by the Texas Water Development Board. The GAMs model aquifers for steady-state and varied pumping conditions. Both types of state-led models take into account regional differences.

Region M has available data within the conjunctive components, but according to their regional water plan, has not yet designed specific conjunctive strategies. Therefore, analysis of the Region M overall goals as compared to possible and achievable conjunctive management goals is the first step in realizing conjunctive strategies in their planning targets. As the region has experienced extreme drought conditions in the late 1990's and the early part of this century, one approach is to optimize groundwater pumping during seasons of low flow. Another approach for growing urban centers is to design and implement aquifer storage and recovery systems, to reduce municipal use of surface waters or to store permitted waters for times of low flow.

Once region-appropriate conjunctive goals are set, review of conjunctive criteria will help determine strengths in existing conditions for viable conjunctive management and gaps in accessible data and information. The criteria are listed in Table 7.1. As noted above, the Region M water planning group has access to a great deal of pertinent information, but it has yet to be analyzed in the context of recognized conjunctive strategies and goals. In particular, having available water models and economic analyses is a powerful, cost-effective tool for decision-making. At this stage of assessing conjunctive options, a key decision point is cost projections, part of the 2010 water planning process. Therefore, utilization and adaptation of available cost-benefit analyses for water resources in the region will be important to the water planning team.

The criteria and inputs in Table 7.1 provide a framework for evaluating the available data, information, site-specific issues, and comparison of scenarios to desired water management goals. As an example of using this framework, the conjunctive strategy of aquifer storage and recovery (ASR) is applied due to its specific nature and

localized system specifications. However, it is likely that the Region M planning team would consider multiple conjunctive strategies in the context of different goals, needs, issues, and variations of hydrology, geography, and population densities throughout the region.

Using information from the Region M water plans (Region M 2006; Region M 2010) Table 7.1 shows the key components and criteria of the framework and the inputs that address each criterion within the example of an ASR system. The ASR approach is one of several possible conjunctive strategies and is chosen so as to simplify inputs and serve as an example of the framework's application. The example inputs are specific to Region M, but for brevity do not list all appropriate data and information.

General results suggest the following:

- The inputs indicate that the majority of information is available for consideration of the framework components and criteria. Thus, costs of considering and planning conjunctive strategies in Region M can be minimized.
- The selected conjunctive approach is an ASR to be designed and implemented for a bounded location such as an urban center or an irrigation district. Physical water factors in Region M are similar to those of the El Paso managed aquifer recharge system, including brackish water quality. Again, costs of initial evaluation can be minimized through utilization of the El Paso system concepts, limitations, design, implementation, and operations over two decades.
- An ASR system will require hydraulic testing of the aquifer system for storage and recovery design (NRC 2008; Pyne 1995). The site-specific tests would be used to finalize possible designs and outputs of the system as well as assess

closeness of fit between desired water management targets and the efficiency of the ASR design.

- By its nature of using groundwater storage, an ASR may support Region M in its stated goal of addressing water transfers between agricultural and urban uses. An ASR can be designed to store water rights permitted to agriculture and used during low surface water flows or droughts by both entities. Under this scenario, funding of the ASR by urban water users, for the benefit of having access to stored waters during water stressed conditions, would be important to bridging the conflicts between competing water uses in the urban and agricultural communities. It is important to note that an ASR is unlikely to store sufficient volumes of water to supply the majority of agricultural demands.
- The framework provides a baseline for a planning team to compile, assess, and balance key conjunctive components and criteria. While a balanced and prioritized baseline is not possible without identifying and evaluating very specific data and issues, the framework performs the function of record-keeping and supports the flow of information between components and criteria.

At this point in the evaluation the planning team would assess and re-evaluate possible cost impacts and technical issues. A list of priority concerns that are specific to the region, the water management goals and targets, and the selected conjunctive strategies would be part of the strategy development. Realistically, the final decision on a “yes or no” to conjunctive management would be finalized at the next level of a water balance model and cost estimates. The model would ideally be adapted for use from existing model and be specific to the region with projections demonstrating closeness of

fit between desired water goals and modeled projections. However, use of the framework supports identification and evaluation of potential strengths and weaknesses of the strategy and a balance among all the conjunctive strategy components and ensures that possible interactions between factors are part of the planning team's evaluation.

In summary, the conjunctive strategy framework is based on previous and/or existing conjunctive strategies and programs rolled into one approach but is developed such that site-specificity takes precedence in evaluating future conjunctive strategies. Its applicability is founded in a large body of research studies, active conjunctive programs, and results addressed through this research. The applicability is demonstrated through its usefulness to communities such as found within Region M that are interested in conjunctive management, but have not yet evaluated the details necessary to informed decision-making about conjunctive strategies.

Transboundary Conjunctive Management

As the river border of Region M is adjacent to Mexican communities, industries, and agriculture, the difficulty in establishing transboundary conjunctive water supply programs is apparent. While three of the hatch-marked regions on Figure 7.1 are bi-national, none of these regions are anticipated to share transboundary water supply projects in the near future. The fundamental reasons for the lack of such projects are not technical, but political and legal in nature. Transboundary, shared water supply programs might bring undesired challenges to recognized international treaties and agreements. The international Rio Grande treaty of 1944 allocated specific quantities of Rio Grande waters to the United States and Mexico. Since that time, multiple communities, agriculture, and industries developed multiple communities, agriculture, and industries

develop on both sides of the border, predicated on the legal basis to existing water rights. Bi-national projects concerned with water quality, human health, and the environment are established on both sides of the border and demonstrate mutual benefits to the bi-national communities. Water supply, however, is a different situation. The legal, institutional, and societal barriers would indeed be difficult for conjunctive or other transboundary water projects to surmount, although not impossible.

It is far more likely that conjunctive strategies, where appropriate for a region in terms of goals, water needs, and supporting structures without undue pressure on ecosystems, biota, and habitats, may be pursued, funded, and supported by a community. An excellent example of separate arrangements is the El Paso/Cuidad Juarez area. El Paso is actively pursuing a variety of water management strategies and programs, as summarized above in the discussion of the Far West Texas Regional Planning Group's conjunctive strategies, while Cuidad Juarez primarily uses groundwater and their portion of treaty-allocated Rio Grande waters. As well, Cuidad Juarez plans increased pumping from the Mesilla Bolson shared by northern Chihuahua and southern New Mexico. Under these conditions, El Paso has the socioeconomic backing to fund different programs such as brackish water desalination, managed aquifer recharge, and tertiary treatment of wastewaters, while Cuidad Juarez has an infrastructure that supports increased use of groundwater.

Shared, binational management of surface water and groundwater through an extensive conjunctive program between El Paso and Cuidad Juarez may not be feasible under current legal and political conditions. However, shared management of a simpler system, one that targets the storage potential in aquifers, might be possible in the future.

One of the strong points in conjunctive management is the natural storage potential under appropriate aquifer conditions. El Paso's managed aquifer recharge demonstrates the long-term viability of a system in the Far West Texas region. Aquifer storage and recovery may be possible in the lower Rio Grande Valley region on both sides of the border through two injection and recovery systems, operating under a transboundary agreement for groundwater management. Even under differing water laws, there is precedent for shared management of aquifers, as demonstrated with the management of the Guarani Aquifer in South America (Kemper et al. 2003; IHP 2001). Agreements between four countries, Argentina, Brazil, Paraguay, and Uruguay, have been made possible through recognition of the tremendous potential inherent in the large-scale, productive Guarani aquifer. The four countries were aided through United Nations Global Environmental Facility funding. While difficult to finalize in terms of funding and accord on water ownership, a transboundary agreement for aquifer management via ASR strategies in the lower Rio Grande valley has the potential to provide significant benefits to both sides of the border in terms of increased water supply and stability.

Conclusions and Recommendations

The goal of this research and its conjunctive strategy framework was to facilitate informed, broad approaches to understanding and applying conjunctive management strategies. A framework for decision-making was prepared for accessibility and applicability, regardless of geographic location or conjunctive strategy. The Rio Grande basin of the southwestern United States is a large-scale watershed with unique natural features, growing population centers, transboundary relationships, and ongoing water concerns in semi-arid to arid environments. Due to the basin's varied geography,

population centers, agricultural regions, and distinctive ecosystems, the basin was selected for research of applicable conjunctive management strategies. Several programs have been implemented in the basin and provided information on possible conjunctive approaches. Information and data concerning one location in the basin, the lower Rio Grande valley, were input into components and criteria of the conjunctive strategy framework.

The results indicate that a majority of necessary information was available for consideration of conjunctive strategies, thus offering the opportunity to implement conjunctive strategies with minimized time to operations and minimized planning and design costs. Application of the conjunctive strategy framework provided a baseline for a planning team to evaluate and prioritize factors important to the region so as to advance to the final decision stages of water balance modeling and cost assessment. Evaluation of an example conjunctive approach, an ASR, showed similarities to those of a well-established managed aquifer recharge system in the El Paso municipality of the basin, particularly with regard to brackish water quality. Conjunctive strategies such as ASR systems may aid in addressing conflicts of water transfers between agricultural and urban uses through beneficial funding mechanisms and advanced conflict resolution measures

Conjunctive management strategies are site-specific, but rather than being a limitation, the programmatic approaches to conjunctive use of the past are now becoming the targeted, local-control, flexible and adaptable strategies of the near future for water management. The conjunctive strategy framework is developed to support water management and planning teams to efficiently and thoroughly explore conjunctive

alternatives to traditional surface water storage (reservoirs) and conveyance. This research demonstrates the efficacy of this framework approach.

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Map prepared by Kristina Tower, River Systems Institute, Texas State University-San Marcos

Figure 7.1 Map of Rio Grande Basin and Conjunctive Programs

Table 7.1 Conjunctive Management Criteria Simplified for Lower Rio Grande

Conjunctive Components	Decision-Making Criteria	Lower Rio Grande Valley – Example Inputs
<p>Conjunctive Management</p>	<ol style="list-style-type: none"> 6. Program goals 7. Specify boundaries of conjunctive program. 8. Identify options for local/regional control of program. 9. Identify and use available data & models to extent possible. 10. Build in adaptive processes. 	<ol style="list-style-type: none"> 1. Major Region M goals (draft, 2010): Increase water supply in times of drought; address water transfers from agriculture to urban 2. Conjunctive program boundaries: ASR, urban or irrigation district design, implementation, & operations 3. Municipality, irrigation district, or shared program local/regional control: utilize to-be-determined volume of water rights & leases for storage. Begin identification of funding mechanisms at local level. 4. Available data & models: Large volume of research studies, data, and models exist for following components of conjunctive management 5. Adaptive processes: SW and GW – monitoring data feedback. Ecological systems – monitor targeted species. Financial – project tracking across conjunctive components and against model projections. Social/stakeholder – feedback forums and educational cross training
Quantitative Components		
<p>Regional Water System</p>	<ul style="list-style-type: none"> <input type="checkbox"/> Identify optimal SW and GW sources with appropriate flow and storage characteristics. <input type="checkbox"/> Identify existing infrastructure, and its components that may be available to a conjunctive program. 	<ul style="list-style-type: none"> <input type="checkbox"/> Rio Grande flows & models well documented, as are aquifer systems within region. Gulf Coast aquifer system has potential in lower layers for ASR. [Carrizo-Wilcox and Queen City-Sparta aquifers not considered in this example.] Brackish GW issues can be addressed in similar manner to those dealt with in the El Paso & Hueco Bolson ASR system. <input type="checkbox"/> Extensive SW conveyance system between irrigation districts and farmers; however, open ditches leak to the subsurface. Municipal water wells known, but agricultural wells and data require better location, withdrawals, and historic use. Amount of infrastructure that may be available to a conjunctive system to be determined through comparison of existing legal contracts and willingness of water use groups to support additional conjunctive management infrastructure usage of existing conveyance and storage systems.

Table 7.1 continued		
Conjunctive Components	Decision-Making Criteria	Lower Rio Grande Valley – Example Inputs
Surface Water (SW)	<ul style="list-style-type: none"> <input type="checkbox"/> Typically primary source of water supply with infrastructure. Identify major SW characteristics. <input type="checkbox"/> Degree of conjunctive management that can be developed into existing water supply program and infrastructure. 	<ul style="list-style-type: none"> <input type="checkbox"/> Rio Grande is primary source; flood control, storage, and recreation part of Falcon Reservoir operations. Flow and channel characteristics studied, identified, and modeled in numerous research and technical reports. <input type="checkbox"/> Conjunctive/ASR management as part of existing system or separate to be determined through finalization of project goals. Additional financial ramifications should additional infrastructure be required rather than utilization of existing infrastructure.
Groundwater (GW)	<ul style="list-style-type: none"> <input type="checkbox"/> Identify appropriate GW storage and retrieval characteristics of aquifer, and its extent. <input type="checkbox"/> Identify available GW water supply infrastructure. Additional well and conveyance infrastructure may be needed. 	<ul style="list-style-type: none"> <input type="checkbox"/> Gulf Coast aquifer system is well studied. Three hydrologic strata, one of which is a confining layer, offer options for ASR in different locations. Brackish waters in the aquifer require treatment prior to use, so storage of waters in the aquifer would need similar water quality or sufficient storage under pressure to reduce mixing. Lessons learned during operation of the El Paso ASR are most likely applicable. <input type="checkbox"/> Number of municipal production and irrigation district wells known, but number of irrigation wells on private land and the degree of piping that might be available for a conjunctive project are estimated. For ASR implementation, technical design must evaluate well injection and recovery zones. Additional conveyance to and from an ASR system is probable and must be included in analysis of ASR strategy and goals.
Ecosystems	<ul style="list-style-type: none"> <input type="checkbox"/> Identify major ecosystems, species of concern, and habitats. <input type="checkbox"/> Build in ecosystem / habitat needs and environmental flows as water uses of the region. 	<ul style="list-style-type: none"> <input type="checkbox"/> Region M has at least 11 distinct biotic (terrestrial vegetation) communities and 6 nature reserves and refuges. A wildlife corridor is being created along the river through land purchases and conservation easements. <input type="checkbox"/> Environmental flow requirements are under state-led studies for targeted areas of Texas. Draft recommendations are anticipated for 2010.

Table 7.1 continued

Conjunctive Components	Decision-Making Criteria	Lower Rio Grande Valley – Example Inputs
<p>Economic / Financial</p>	<ul style="list-style-type: none"> <input type="checkbox"/> Identify cost/benefit analyses on water supply system, if available. Add information as necessary using available data <input type="checkbox"/> Analysis of historic and current water (SW & GW) prices, and tipping point of use between sources. <input type="checkbox"/> Identify funding options 	<ul style="list-style-type: none"> <input type="checkbox"/> Cost/benefit analyses for water management strategies in the Region M 2010 plan are under construction. Whether these analyses include ASR, or ASR costs & benefits can be adapted for use in the cost/benefit analysis, can be determined in 2010. <input type="checkbox"/> Water costs can be reviewed at the irrigation district level or by municipality. In both cases, costs of SW & GW sources are typically mixed. <input type="checkbox"/> Funding for ASR: if designed for municipal storage and recovery of water allocations, bonds or similar form of public borrowing is feasible. If ASR is part of irrigation district water management, costs of design, implementation, and operations may be a combination of long-term loans and fees assessed on water use members. Funding mechanisms used by the El Paso ASR system can be explored as an example.
Qualitative Components		
<p>Legal / Institutional</p>	<ul style="list-style-type: none"> <input type="checkbox"/> Review established water rights & permits. Review legal framework to store and retrieve SW & GW. <input type="checkbox"/> Identify or create process for conflict resolution between water agencies and other water-related entities. 	<ul style="list-style-type: none"> <input type="checkbox"/> Adjudicated water rights on file with TCEQ. Identify water rights currently under conflict. WAM model for the region calculates water allocations for the system. Water storage and retrieval well-established for SW system, but GW storage and recovery rights less certain. ASR’s in other regions of Texas are permitted through underground injection rules; permitting process will be one of several major tasks. <input type="checkbox"/> Conflict resolution agreements can be initiated through 1) identification of water user groups and existing water rights conflicts (see item above); 2) successful resolutions in the region; 3) facilitation of discussions between groups on mutual benefits through ASR implementation; 4) initiate Memorandum of Agreement between water user groups.

Table 7.1 continued		
Conjunctive Components	Decision-Making Criteria	Lower Rio Grande Valley – Example Inputs
Societal / Stakeholders	<ul style="list-style-type: none"> <input type="checkbox"/> Identify water users with historically high usage rates: irrigated agriculture, urban (combination of municipal, industrial, other). <input type="checkbox"/> Identify projections of population or irrigated agriculture for specified timeline, with associated increases in water demands. <input type="checkbox"/> Participatory approach is utilized to understand and quantify the level of support for program. 	<ul style="list-style-type: none"> <input type="checkbox"/> Water users, uses, and volumes identified in Region M water plan (2006; 2010) – irrigation, municipal, rural, industry, mining, livestock. <input type="checkbox"/> Population growth and water use per sector including irrigated agriculture, urban, industry, mining, livestock are in the Region M water plan. Projections include current and 20-year projections. <input type="checkbox"/> Participatory approach has been established through Region M water plan.

CHAPTER 8

THE FUTURE OF CONJUNCTIVE WATER MANAGEMENT

Focusing on conjunctive management of surface water and groundwater, this research addressed significant factors that support this strategy as long-term, viable, and successful at accomplishing multiple goals. While the concept of using one water source when the other is at a low flow condition might seem straightforward, implementing programs to optimizing the use of each source for more efficient, and possibly more conservative, water use, is not as simple. No water management program meets the adage of “faster, better, cheaper,” and every approach has tradeoffs as well as strengths and advantages. This research targeted the major components of conjunctive management, and the relationships between those components, and created a conjunctive strategy decision framework to aid planning teams, decision makers, and stakeholders to better understand conjunctive management. As well, an improved understanding of water management goals that can be addressed through the strategy, consideration of multiple components, criteria, factors, and evaluation of benefits, costs, and tradeoffs were all part of the framework’s design. The resulting decision framework supports evaluation of conjunctive strategies in such a manner that programs manage the water resources, in contrast to the issues managing the program.

The following sections summarize the dissertation results, discuss the advantages and weaknesses of conjunctive strategies, and provide a look into the future of conjunctive management through models and a cost comparison.

Summary of Results

The primary goal of the research was to determine the factors that best support conjunctive management. Four major components were identified in the literature – physical water systems, economics, water laws, and societal issues. The objectives through which to determine primary supporting factors of conjunctive management were: 1) evaluation of components, criteria, and external factors; 2) creation of a decision framework to support policy decision-making with regard to conjunctive management options; and 3) application of the decision framework in the Rio Grande basin.

The first objective was realized through evaluation of conjunctive management components. Two major components, physical water systems of surface water and groundwater, were researched through extensive evaluation of existing models and programs. In Chapters 2 and 3, research focused on major characteristics of physical water system and economic-conjunctive models. The reviewed models and programs targeted physical water and/or economic systems and issues through conjunctive strategies. Analysis revealed common parameters that were similar in nature between the physical and economic studies. The other factors noted were parameters unique to each study, considerations such as a wide variety of water use issues beyond the major uses of irrigated agriculture and municipal, and wide ranges of applicable hydrologic and study data. Moreover, gaps were identified in the programs concerning realistic stakeholder inputs, possible impacts or benefits to ecosystems, and inclusion of water conservation

measures. Overall, the results of model evaluations indicated that a broad variety of geographic locations and water management situations and goals were not only applicable, but appropriate and economically efficient, for utilization of conjunctive management strategies. The flexibility inherent in conjunctive strategies as well as the benefits afforded through efficient utilization of surface water and groundwater flows and storage provided additional strengths to consider.

Water laws provide a critical framework that can support or discourage certain water management approaches. Having previously determined that water laws can be an impediment for future conjunctive management programs, this research included a review of water laws in five western U.S. states, as a means of identifying legal obstacles. Selection of these states was based on the different paths each state used to establish surface water and groundwater laws and rules. Review and analysis of water doctrines, statutory and case law relevant to the development of conjunctive management, and example conjunctive programs in each state indicated not so much obstacles, but rather different paths, to implementing conjunctive strategies. Legal frameworks impacted the evolution of conjunctive programs, but none of the states prevented the development of conjunctive management.

Societal and stakeholder inputs as a major component of conjunctive management was addressed through a survey and informational interviews of researchers and professionals in water resources and management (Chapter 5). Analysis of the survey and interviews results allowed insights into user perceptions of conjunctive management and overall water management. Due to the low number of responses, the results were not utilized to interpolate data or make projections. However, the results provided

indications and insights into how the societal component of conjunctive management can affect other factors. More than any other indicator, the evaluation results showed that every professional had a different opinion on the definition, uses, and application of conjunctive management. It is likely that disparities in agreement between professionals on conjunctive strategies will carry over into ambiguities and imprecision in water policy and management decisions.

The above results, analyses, and identification of gaps were used to create a new decision framework for evaluation of conjunctive strategies. The framework involved creation of a new conceptual model, development of criteria per component to establish a basis for decision-making, and a decision matrix comprised of conjunctive components and external factors. First, elements not consistently identified in previous studies, but which were considered essential to current water management, were recognized. Previously identified as physical water systems, such classification was re-organized in the conceptual model as separate components of regional, surface water, and groundwater systems. The importance of ecosystems, their roles and requirements in any physical water system, and possible impacts on ecosystem due to current and future water management approaches, was recognized as an individual component. Although Chapter 4 focused on the legal issues of conjunctive management, and did not specifically address water institutions, the consequence of the latter was also recognized by placing institutions in the legal component. Thus, the conceptual model incorporated seven major components of regional, surface water, and groundwater systems, ecosystems, economic/financial issues, legal/institutional frameworks, and social/stakeholder input.

The minimum criteria necessary to plan and design a conjunctive management strategy were developed from analysis of the major components, with particular attention on the implications of the common and unique parameters identified in Chapters 2 and 3. The criteria were compiled for each component. Due to the importance of identifying potential program goals, targets, available information, and the need for future flexibility under unknown variability in site-specific and climatic conditions, the criteria for conjunctive strategy development was emphasized and used as a basis for evaluating possible conjunctive management goals.

The conjunctive decision framework was prepared to establish and support water management decisions using conjunctive strategies. Based on the survey and interview results (Chapter 5) that indicated the lack of definitive or shared understanding of conjunctive management, the decision matrix was developed to inform, as well as guide, planning teams through significant factors that may or may not support their identified conjunctive goals and targets. The decision matrix detailed the relationships between the seven major components and significant external factors of the planned program, the involved watershed, physical water system characteristics, infrastructure, water uses of the region, modeling and optimization, and parameters identified through evaluation of water balance and economic conjunctive models. Utilization of the framework will facilitate a solid understanding of potential conjunctive goals and strategies in relation to the major components and factors in a site-specific manner. Further, the matrix was developed for use in any watershed, regardless of location. The focus was entirely on understanding and developing conjunctive strategies for future water balance modeling

and decision-making as to the financing and implementation of a conjunctive program design.

To highlight the applicability and relevance of the framework, the criteria base was applied to a selected region in the Rio Grande basin of the southwestern United States. In general, the basin was selected due to a range of distinctive characteristics with regard to water management. These characteristics included development of urban and agricultural communities along and near the main stem of the river, the unique geographical and ecological features throughout the basin, and the occasionally severe water-stressed conditions which varied from floods to droughts. Existing conjunctive programs in the basin provided three examples of how conjunctive programs developed in response to different goals, state water laws, and groundwater systems. The three programs also provided information on conjunctive strategies, targets, and program operations in the basin.

The lower Rio Grande valley region was selected for application of the framework. Information, data, and data gaps were input into the framework's compiled list of components and criteria. Analysis of results indicated that the majority of information necessary to evaluate a conjunctive strategy was available for consideration of conjunctive strategies. Evaluation of an example conjunctive approach, an aquifer storage and recovery (ASR) system, showed similarities to the El Paso ASR in the Far West Texas region of the basin. In particular, "lessons learned" from the El Paso case with regard to brackish water quality in the Hueco Bolson appear to be highly applicable to designing an ASR for the brackish waters of the Gulf Coast aquifer system in the lower Rio Grande valley. In addition, the El Paso ASR program operation metrics and

financing mechanisms allowed a favorable comparison for developing an ASR in urban/agricultural areas of the valley, therefore potentially reducing overall program design and operation costs. A water management region noted in the recent draft of the State of Texas Region M water planning document was conflicts of water transfers between agricultural and urban uses. Conjunctive strategies such as ASR's may aid in addressing such conflicts through beneficial funding mechanisms and progressive conflict resolution actions. Testing of the framework for relevancy and applicability demonstrated that the framework provides a thorough, definitive baseline for a planning team to evaluate and prioritize factors important to that planning region, so as to advance to the final decision stages of water balance modeling and cost assessment.

Conjunctive Goals and Targets

The conjunctive water management concept has been applied to many locations and varying site conditions. Results of this research indicate that a useful approach for the future is the concept as a strategy, rather than a program, thereby advancing the concept from one with limited application to a strategic practice. The concept then becomes a wide lens through which to critically view and analyze future water management alternatives, with groundwater in a critical role as a water supply supplement and storage partner to surface water.

Chapter 7, which discussed application of the conjunctive decision framework to the lower Rio Grande valley, highlighted water management goals and targets as being of fundamental importance for outlining the most appropriate conjunctive strategy for a specific site or region of water uses. Application of the conjunctive concept is relevant to multiple goals, including the following:

- Augmentation of low surface water supplies with extracted groundwater;
- Aquifer storage and recovery;
- Prevention or mitigation of aquifer overdraft through artificial recharge or optimized use of surface water supplies in conjunctive with groundwater extraction;
- Management of interconnected surface water and groundwater flows through “in-lieu” augmentation programs or targeted water balance use of surface water and groundwater;
- Mixing of water sources with varying water quality to accomplish water quality goals for water districts and utilities;
- Prevention or mitigation of brackish seawater intrusion in coastal regions;
- Management of surface water and groundwater sources to prevent or mitigate land subsidence.

Targets are a measured, quantified means of defining the optimal withdrawal and storage of surface water and groundwater to accomplish a water management program’s set of goals. As reviewed in this research, conjunctive program targets displayed a broad range of both singular targets and a combination of targets, including water balances and instream flow requirements. The following are the targets identified through review of optimization approaches in conjunctive models:

- Physical water balances and projected scenarios through application of numerical models of surface water and groundwater;
- Scenarios of water flow gains and losses, compared with the associated economic costs and benefits;

- Minimum surface water levels or flows that act as a trigger point to curtail the use of surface water and initiate, or increase, extraction of another water source, such as groundwater to meet water supply needs;
- Comparison of basin inflows to mean flows during historic periods of drought;
- Economic targets specific to a study region or conjunctive program;
- Minimum water quality standards.

The conjunctive decision framework discussed in Chapter 6 emphasizes the importance of goals, and the relative balance between major components. The framework does not attempt to define one approach to conjunctive goals, targets or modeling, because the research results clearly recognize that multiple approaches may be appropriate for any site-specific water management program. The best conjunctive strategy is one that ‘fits’ the region, including the physical water and ecologic system characteristics, and the water needs and socio-economic conditions. The framework provides a detailed path to put conjunctive strategies into fast-track planning and future implementation.

Advantages and Disadvantages

In conjunctive water management, clearly-defined goals, targets, boundaries of application (geographic, water uses, etc.), benefits, and limitations of a planned program will aid in increased public understanding and support. Chapter 5 involves societal and stakeholder concerns, and highlights the ever-increasing importance of public participation in water management decisions and financing, particularly with regard to better understanding water resources and limits, projected water balance scenarios, and possible impacts and implications for ecosystems. In regions of groundwater inclusion in

the water supply, a topic that water resource managers continue to emphasize through public outreach and education programs is groundwater as an active, managed water source with characteristics that are different in time and space from those of surface water. Groundwater in conjunctive management, however, can offer distinct improvements in long-term reliability, water storage over time, and support.

Several technical papers have reviewed the advantages, benefits, costs, and constraints related to conjunctive management programs. Table 8.1 lists advantages and benefits identified by researchers and water management professionals, while Table 8.2 highlights their disadvantages, costs, and constraints. The number of points in these categories is another reminder that while conjunctive strategies are flexible, they are not limitless. The benefits from conjunctive programs may be considered worthwhile, but the tradeoffs must be a part of the overall program assessment, planning, design, and implementation.

Water Balance Modeling

While not the focus of this research, water balance modeling provides critical information for viable conjunctive management. As importantly, appropriate modeling will support decisions about the conjunctive system and its adaptability to unforeseen changes in site, climate, and/or water supply conditions. Models must adequately address program goals and targets, represent surface water movement and groundwater structures and flows within quite different timing and spatial scales and, depending on the program targets, deal with other constraints such as economic limits, ecosystem flows, and legal and institutional requirements. While highly-complex models may provide the best resolution for the physical water systems, they may be difficult to run or adjust, except by

a few experts in the field of modeling. Simple models with broad assumptions may not adequately represent the water systems, and fail to provide useful, cost-efficient, or realistic scenarios by which to implement and adapt a water management system. The site-specific requirements for long-term, sound decisions of conjunctive management are no less true than for the associated models.

Cost Evaluation

Because conjunctive management programs are specific by the nature of their goals, targets, surface water systems, aquifers, socio-economic conditions, and other factors discussed throughout this research, the associated costs can be difficult to compare. A technical paper from the Los Angeles area, however, assessed costs for nine strategies of water management that were considered applicable to that region (LAEDC 2008), with the comparison being summarized in Table 8.3.

The cost summary, underlying assumptions, and supporting cost calculations are pertinent to the Los Angeles region, and cannot be carried over to other programs with any reliability. A relative comparison between the different strategies and associated costs, however, suggests the following point is relevant to conjunctive management: Initial and long-term (30-year) costs for groundwater storage strategies rank third, behind urban water conservation and local stormwater capture. Due to the size of the urban population and developed acreage, a comparative cost advantage may be possible for other large urban areas. The large volume of irrigated water used for agriculture in other portions of the state are not addressed for potential savings in water conservation. The potential increases to water supplies, however, puts groundwater storage potential for the basin just behind the potential water savings attributable to urban water conservation.

Effectively, groundwater storage and the calculated assumptions of additional wells, conveyance, infiltration galleries or injection wells, are substantially less than adding new surface water dams and reservoirs or less conventional approaches such as desalination. With regard to relative costs of implementing a conjunctive program with groundwater storage, the economic advantages to a community for a reliable, long-term source of water along with optimized, and hopefully reduced, use of surface water, has definite benefits to recommend serious consideration of conjunctive strategies.

Concluding Remarks

This research has approached the question of factors that support, or discourage, conjunctive management from multiple disciplines. Gaps identified throughout the research and evaluations can succinctly be summarized as a need for a cohesive approach to understanding, planning, and implementing conjunctive management, while also working within recognized limitations and tradeoffs. The result is creation of a conjunctive decision framework pertinent to considering conjunctive strategies and water management goals, regardless of location or site-specific characteristics. Application of the framework is demonstrated to allow in-depth analysis of the various components, factors, and potential benefits and impacts from implementation of a conjunctive program. Compelling reasons to consider conjunctive management are its flexibility, the applicability for small- and large-scale projects, its relative cost effectiveness, proven long-term viability, increased management of groundwater, particularly at the local and groundwater basin level, and incorporation into existing water management programs. Inclusion of environmental flows and water conservation targets in models are also considered highly beneficial to sustainable water management. In addition, conjunctive

optimization can occur through multiple technical approaches that fit site-specific needs. Finally, the information, data, and decision framework presented in this research bridge existing gaps in understanding and implementing viable, long-term conjunctive programs.

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Table 8.1 Advantages and Benefits

Clendenden 1955; Todd & Mays 2005	Advantages *
	Greater water conservation Smaller SW storage (and therefore decreased evaporation loss) Smaller SW distribution (if spatial distribution of wells increases) Decrease drainage problems Reduced canal lining (can use seepage as artificial recharge process) Greater flood control Integration with existing infrastructure Can develop in stages Greater control over SW outflow When hydropower is involved, can optimize SW releases Smaller volume of water distribution will decrease chances of weed spread Better timing of water distribution
Coe 1990	GW Storage Advantages as Compared to SW Storage
	No construction costs Fewer sedimentation issues No evaporation losses except in cases of shallow GW Little land area required for operation Not subject to eutrophication Little impact to aquifer under appropriate management Little to no disturbance of archaeological or cultural sites No disturbance of in-stream fisheries or recreation Advantages of Conjunctive Use Increase in water supply yield Can offset maldistribution of runoff GW basin may allow water storage closer to users Smaller SW system possible if wells are widely dispersed Supports water conservation in times of low water supplies through access to GW storage and extraction Can decrease need for more expensive SW storage/dams/reservoirs Can utilize full or extracted GW basins Can reduce drainage programs in areas where wells act as vertical drains Can use unlined canals as source of GW replenishment/recharge Can provide flood control space in reservoirs through transfer of waters to GW basins
Reichard & Raucher 2003	Benefits
	Buffer value between utilization of water sources GW storage value GW basin conveyance value Treatment value of GW basin Reduced pumping lifts Subsidence control Seawater-intrusion control “Nonuse” benefits

Note: Conjunctive use programs typically assume that some water delivery structures (pipes, wells, canals, aboveground storage) are in place.

Table 8.2 Disadvantages and Costs

Clendenden 1955; Todd & Mays 2005	Disadvantages
	Less hydroelectric power (if conjunctive use program has smaller SW reservoirs)
	Greater power consumption with increased well pumping
	Decreased pump efficiency with increased number of wells
	Potential for increased GW salinity through artificial recharge into vadose zone
	More complex water management operations
	More difficult cost allocation
	Increased GW pumping may cause land subsidence
Coe 1990	Disadvantages
	GW pumping, maintenance
	Sedimentation probable in infiltration areas
	Accumulation of saline residues in cases of shallow GW evaporation loss
	GW susceptible to point & nonpoint source pollution
	Over-extraction can cause loss of storage space through decreased porosity
	Constraints to Conjunctive Use Implementation
	Inadequate water supply for GW recharge
	Aquifer storage space is insufficient
	Infiltration/percolation rates are inadequate for basin recharge
	Land/appropriate sites for GW recharge may not be available or affordable
	Existing wells are not adequate for GW withdrawals during drought
	New upstream reservoirs, or change in operations, can reduce water supply or water quality
	Water rights and downstream uses must be taken into account
	Costs of GW overextraction can include brackish water or land subsidence mitigation
	Repeated over-recharge conditions into vadose zone can cause soil salination
	Conjunctive use may be restricted by existing water programs
	Disparity in SW and GW prices can discourage use of more expensive water source
	Funding may be different for SW vs. GW source development (public for SW; individual use for GW)
	Lack of coordination between multiple water agencies may hinder program effectiveness
Reichard & Raucher 2003	Costs
	Well installation and development
	GW pumping
	Water injection into wells
	Potential water quality degradation
	Decreased aquifer capacity in cases of injection and decreased porosity
	Effects on ecosystems from water withdrawals and reduced flows
Other	Costs
	Hydropower facility design, installation, operations, maintenance
	Facilities and physical conveyance
	Energy – pumping, water conveyance
	Artificial recharge program costs
	Individual costs of water use
	Social costs of water use
	Water treatment
	Wastewater recycling

**Table 8.3 Cost Comparison Summary of Water Strategies, Southern California
(from LAEDC, 2008)**

Strategy	2025 Water Potential Increases in Water Supply (thousand acre-feet)	Timeframe (years)	Initial Capital Cost (\$ million)	30-Year Treated Costs (\$ per acre-foot)
Strategies to Replace or Augment Imported Water				
Urban water conservation	1,110 +	0-2	\$0	\$210
Local stormwater capture	150 +	3-5	\$40 - \$63	\$350 +
Recycling	450 +	6-10	\$480	\$1,000
Ocean desalination	150 +	6-10	\$300	\$1,000 +
GW desalination	To be determined	6-10	\$24	\$750 - \$1,200
Strategies to Increase Imported Water				
Water transfers (agriculture to urban)	200 +	1-5	n/a	\$700 +
Strategies to Increase Reliability				
Inter-agency cooperation	To be determined	0-5	“low”	n/a
GW storage	1,500 +	3-5	\$68 - \$135	\$580
SW storage	0	10 +	\$2,500 and greater	\$760 - \$1,400

APPENDIX A: PHYSICAL WATER SYSTEM MODELS – INFORMATION AND
DATA COMPILATION

Table A.1 Background Information on Selected Water Balance Models

Citation	Location	Study Area	Data Records	Problem	Primary Water Users
Barker et al. 1983	Arkansas River, KN	110,000 acres	10-yr study period	60% decrease in river flows; evaluate streamflow vs. pumping rates	Agriculture, small municipal
Barlow et al. 2003	Alluvial valley stream-aquifer system, RI	49 km ²	56 yrs of flow data; 6 yrs of GW pumping data	Evaluate tradeoffs in river flows vs. GW withdrawals	Municipal, industrial, fish hatcheries
Booker et al. 2005	Upper Rio Grande Basin, southwest U.S.	Basin from head-waters, CO to El Paso, TX	Study period: 6 yrs. Stream records: est'd to > 100 yrs	Create model to project scenarios that address over-allocation, droughts, & competing demands	Agriculture, municipal, environmental
Dai & Labadie 2001	Arkansas River, CO	Basin from head-waters to eastern CO	<i>N/A</i>	Examine WQ (salinity) due to excess water & inc. GW levels	Agriculture, small municipal
Draper et al. 2003; Jenkins et al. 2004; Pulido-Velazquez et al. 2004	Central Valley, Bay area, and southern CA	Central Valley, Bay area, and southern CA	Historic 72-yr flow record (1922-1993)	Use of CALVIN model to simulate management of > 50 Bm ³ , 3000 agencies, districts	Agriculture (24 demand areas), urban (19 demand centers), environmental (39 flow areas)
Fleckenstein et al. 2004	Cosumnes River, CA	Basin = 3,300 km ²	Stream flow records = 41-74 yr; 26-year simulation period	GW pumping decreased base flow needed for fall salmon runs.	Agriculture, municipal, environmental
Fisher et al. 1995	East Bay Municipal Utility District (EBMUD), CA	Much of Alameda & Contra Costa counties	Inflows, 62 yrs (1972 - 1989)	Evaluate options for droughts: water purchases or conjunctive use	Agriculture, flood control, urban (consumption ~ 220 mgd)

Table A.1 (continued)					
Citation	Location	Study Area	Data Records	Problem	Primary Water Users
Peranginangin et al. 2004	Singkarak-Ombilin basin, West Sumatra Province, Indonesia	Basin = 2,210 km ² ; two sub-basins.	15-20 yrs data	Lake diversions much greater than available water in system	Agriculture, hydropower, domestic, fish culture, livestock, limited industry, coal washing, thermal power
Reichard 1995	Santa Clara-Calleguas basin, CA	800 km ²	Study period: 15 yrs. Stream records: est'd to > 100 yrs	Manage water supply, optimal GW pumping, artificial recharge, minimize sea-water intrusion	Agriculture, municipal
Yang et al. 2001	River Shiyang basin, NW China	30,000 km ² (model ~ 8,784 km ²). 2 major basins	9 yrs	Multi-objective optimization to determine best solutions to GW overdraft, salinity, environmental issues	Agriculture, domestic, livestock, industry, forestry

Abbreviations:	Bm ³	Cubic meters, in billions
	GW	Groundwater
	km ²	Kilometers squared
	mgd	Million gallons per day
	N/A	Not available in reviewed publication
	SW	Surface water
	WQ	Water quality
	yr	Year(s)

Table A.2 Surface Water Data Compiled from Selected Models

Citation / Location	Reservoir Characteristics	Canals or Diversions (annual average)	River Channel	Precipitation (annual average)	Flow (annual average)	Surface Runoff or Return Flows	Evapo-Transpiration	Hydraulic Connect to Aquifer	Infiltration	Annual Stream Outflow
Barker et al. 1983 / Arkansas River, KN	50 miles upstream (CO); operations under Arkansas River Compact	3 canals, 26,000 ac-ft	48 mi L, 20 ft avg width; gradient ~ 6ft/river mi	16.5 in/yr (long term avg)	Decrease of 232 -> 85 cfs	N/A	N/A	Y: 65,000 AFY recharge	1.21 ft/d	N/A
Barlow et al. 2003 / Stream-aquifer system, RI	N/A	N/A	3 rivers; streambed conductance (90-1900 m ² /d)	1.5 - 11.9 cm/yr	GW input to stream = 0.74 cm/yr; fish hatchery discharge = 0.06 m ³ /s	N/A	0.53 m/yr	Y: Model specification: 0.03 m ³ /s	N/A	Model value = 1.96 m ³ /s
Booker et al. 2005 / Upper Rio Grande Basin, southwest U.S.	6 major reservoirs; primary purpose is storage & water supply	80-90% irrigation; environmental flow target = 50 cfs (silvery minnow, central NM); treaty = 60,000 AFY to MX	N/A	20 cm in desert areas	1.57 MAF (headwaters)	N/A	N/A	Y: Function of lagged net seepage to river	N/A	N/A

Table A.2 continued

Citation / Location	Reservoir Characteristics	Canals or Diversions (annual average)	River Channel	Precipitation (annual average)	Flow (annual average)	Surface Runoff or Return Flows	Evapo-Transpiration	Hydraulic Connect to Aquifer	Infiltration	Annual Stream Outflow
Dai & Labadie 2001 / Arkansas River, CO	1 major reservoir; several off-stream reservoirs	16 major diversion systems	N/A	10-40 in	N/A	N/A	N/A	Y: Canal leakage, excess irrigation flows	N/A	N/A
Draper et al. 2003 / Jenkins et al. 2004 / Pulido-Velazquez et al. 2004 / Central CA	51 SW reservoirs & associated infrastructure; 50 Bm ³ SW storage	Multiple	Multiple	N/A	Varies	Variable	N/A	N/A	N/A	N/A
Fleckenstein et al. 2004 / Cosumnes River, CA	1 small irrigation reservoir	N/A	1 mainstem, 3 tributaries. Based on isotopic tests, river is seepage-dominated; little to no GW recharge in Oct-Dec season	"Mediterranean" climate; seasonal variations	Seasonal: 0 (late summer) – 2,650 m ³ /s (peak record, 1997)	N/A	N/A	Y: Model term = (gradient x conductance)	35 - 152 Mm ³ , with avg of 89 Mm ³ in DWR study ('62-'69)	Target stream stage = 18 cm, or 0.57 m ³ /s; min flow required to support fish migration

Table A.2 continued

Citation / Location	Reservoir Characteristics	Canals or Diversions (annual average)	River Channel	Precipitation (annual average)	Flow (annual average)	Surface Runoff or Return Flows	Evapo-Transpiration	Hydraulic Connect to Aquifer	Infiltration	Annual Stream Outflow
Fisher et al. 1995 / East Bay Municipal Utility District, CA	1 reservoir (211 KAF) with aqueducts; 2nd reservoir (430 KAF) used for agriculture, flood control	3 aqueducts	Mokelumne River	N/A	N/A	N/A	Key model term: evaporation from reservoirs	Y: Key model term - seepage losses from river	N/A	N/A
Peranginangin et al. 2004 / Singkarak-Ombilin basin, Indonesia	Lake in each sub-basin	Transfer from upstream lake for hydro-power, 682 Mm ³ (13 yrs) or 37.2 m ³ /s/yr	N/A	1.7-2.9 m	Included in model; unknown range	Included in model; unknown range	3.9 - 5.3 mm/d	Y: GW dischg to streams, causing delayed low flows vs. lowest rain-fall months	Y: model terms = vadose & sat'd zone infiltration	Downstream basin (Ombilin River) decrease from 53 to 2-6 m ³ /s

Table A.2 continued

Citation / Location	Reservoir Characteristics	Canals or Diversions (annual average)	River Channel	Precipitation (annual average)	Flow (annual average)	Surface Runoff or Return Flows	Evapo-Transpiration	Hydraulic Connect to Aquifer	Infiltration	Annual Stream Outflow
Reichard 1995 / Santa Clara-Calleguas basin, CA	Upstream reservoir for SW releases (not part of model)	Model considers 5 levels of diversion from river	Santa Clara River	N/A	Re-construction of base flow = 88 ft ³ /s (2.5 m ³ /s)	GW model assumed low Kh = no return flows as part of recharge	N/A	Y: Santa Clara River modeled as source of natural GW recharge	N/A	N/A
Yang et al. 2001 / River Shiyang basin, NW China	Reservoir capacity = 4.7x10 ⁸ m ³ . "Extensive" evaporation	Estimated that 76% of SW is channeled for irrigation	8 rivers in basin; estimated that 65% of flow is from precipitation & 35% from GW	100-250 mm/yr	River flow, 30-yr decrease (5.7 x10 ⁸ m ³ /y to 2.2x10 ⁸ m ³ /y)	N/A	2000 - 3000 mm	Y: Rivers & irrigation ditches recharge GW	N/A	N/A

Abbreviations:

ac-ft	Acre-feet	KAF	Acre-feet, in thousands
AFY	Acre-feet per year	MAF	Acre-feet, in millions
AR	Artificial recharge	m/d	Meters per day
Bm ³	Cubic meters, in billions	m ² /d	Squared meters per day
cfs or ft ³ /s	Cubic feet per second	m ³ /s	Cubic meters per second
cm/s	Centimeters per second	mgd	Million gallons per day
cm/yr	Centimeters per year	mm/yr	Millimeters per year
ft/d	Foot per day	m/yr	Meters per year

Table A.2 continued

Abbreviations continued:

GW	Groundwater	N/A	Not available in reviewed publication
in/yr	Inches per year	SW	Surface water
km ²	Kilometers squared	WQ	Water quality
		yr	Year(s)

Table A.3 Ground Water Data Compiled from Selected Models

Citation / Location	Aquifer Characteristics	Annual recharge	Top of Aquifer	K _h or T	K _v	SY	Storage Coef	ET (water table)	Pump Yields	Total Pumping (avg annual)	Outflow
Barker et al. 1983 / Arkansas River, KN	Unconfined sand/gravel alluvium, bedrock & fault boundaries	74 KAF total: 15 KAF (river), 9 KAF (lateral inflow), 50 KAF (percolation)	0-100 ft (sat'd thickness)	K _h = 800 ft/d, model value; actual varies	N/A	0.14 - 0.2 (input to model grid)	0.17	1,000 AFY, model term	1000-3000 gpm; if saturated thickness > 25 ft, 100 - 3000 gpm	Increase = 18 to 65 KAF, 89 to 160 wells (3 public supply)	12 KAF (lateral flow); 1 KAF (GW loss to river); 11 KAF (GW ET); 57 KAF (pumping)
Barlow et al. 2003 / Stream-aquifer system, RI	Unconfined sand/gravel alluvium, till and bedrock boundaries	Precipitation = 71.1 cm/yr (0.97 m ³ /s over model area); upland GW inflow = 0.55 m ³ /s; WW recharge = 0.03 m ³ /s	36 m (sat'd B)	Avg K _h = 61 m/d (8 - 179 m/d)	Model term: K _{v:h} = 1:5	0.28	3.0 x 10 ⁻⁴	Model calculation = 0.13 m ³ /s	Historic ~ 0.23 m ³ /s over 56 yrs. Current demand = 1.92 Mm ³ (507 Mgal)	18 large capacity wells (14 public supply, 1 industry, 3 fish hatchery), 1.92 Mm ³ (507 Mgal)	0.03 m ³ /s
Booker et al. 2005 / Upper Rio Grande Basin, southwest U.S.	Rio Grande alluvial system, CO to TX	Function of lagged net seepage from river	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table A.3 continued

Citation / Location	Aquifer Characteristics	Annual recharge	Top of Aquifer	K _h or T	K _v	SY	Storage Coef	ET (water table)	Pump Yields	Total Pumping (avg annual)	Outflow
Dai & Labadie 2001 / Arkansas River, CO	Alluvial	Recharged through canal leakage, irrigation return flows	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Draper et al., 2003 Jenkins et al., 2004 Pulido-Velazquez et al., 2004 / Central CA	28 GW basins; 170 Bm ³ GW storage, with ~ 71 Bm ³ used during drought	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fleckenstein et al. 2004 / Cosumnes River, CA	3-aquifer system, Tertiary & Quaternary formations. Model adapted from county model; parameters listed in other reports	River recharge; modeled as deep percolation	2 - 16.7 m	N/A	N/A	N/A	N/A	N/A	2 major cones of depression	Network of 33 public supply & agriculture wells. Model domain pumping = 703 Mm ³	N/A

Table A.3 continued

Citation / Location	Aquifer Characteristics	Annual recharge	Top of Aquifer	K _h or T	K _v	SY	Storage Coef	ET (water table)	Pump Yields	Total Pumping (avg annual)	Outflow
Fisher et al. 1995 / East Bay Municipal Utility District, CA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Peranginangin et al. 2004 / Singkarak-Ombilin basin, Indonesia	Shallow, unconfined aquifer under much of basin	Locally recharged by infiltrated rainfall (<i>parameter in water accounting model</i>)	0.3-15 m below ground level	N/A	N/A	N/A	N/A	N/A	N/A	N/A	<i>Parameter in water accounting model</i>
Reichard 1995 / Santa Clara-Calleguas basin, CA	5 aquifers grouped as 2 systems (upper & lower). Assumed heterogeneous, isotropic, confined flow	Varied per sub-basin: 1 - 113 ft ³ /s (0.03 - 3.2 m ³ /s)	Upper ~ 100 ft (30 m) BSL; Lower ~ 400 ft (120 m) BSL	T = <0.1 to 0.7 ft ² /s	Model grid (< 10 ¹⁰ to 10 ⁻⁸); AR area = (2.5x10 ⁸)	<i>Not applicable</i>	Varied in model: 10 ⁻⁴ to 3x10 ⁻¹	10 ⁻¹ to 10 ⁻⁴	SW+ GW (1984-1989) = 360 ft ³ /s (10.2 m ³ /s)	N/A	N/A

Table A.3 continued

Citation / Location	Aquifer Characteristics	Annual recharge	Top of Aquifer	K _h or T	K _v	SY	Storage Coef	ET (water table)	Pump Yields	Total Pumping (avg annual)	Outflow
Yang et al. 2001 / River Shiyang basin, NW China	2 aquifers with similar vertical K; modeled as 1 sand, gravel alluvial aquifer that is isotropic, heterogeneous	River & ditch recharge ~ 60% of GW; remaining % from lateral inflow, return flow, precip	Saturated thickness = 50-200 m	T = 10 - 6,000 m ² /d	N/A	0.1-0.3	N/A	Yes	> 10,700 irrig wells = 9.37 x 10 ⁸ m ³ . GW overdraft = 4.14 x 10 ⁸ m ³ /y (1978-1991)	Rate of drawdown = 0.25 - 0.57 m/yr	Discharge from springs, evaporation, pumping. GW levels decreased 4-7 m over 40 y; some springs have dried

Abbreviations:

AFY	Acre-feet per year			K _h , K _v	Hydraulic conductivity, horizontal or vertical
AR	Artificial recharge			m	Meter
Bm ³	Cubic meters, in billions			m/d	Meters per day
BSL	Below sea level			m/yr	Meters per year
cfs or ft ³ /s	Cubic feet per second			m ³ /s	Cubic meters per second
cm/yr	Centimeters per year			MAF	Acre-feet, in millions
ET	Evapotranspiration			Mgal	Gallons, in millions
ft	Foot, feet			Mm ³	Cubic meters, in millions
ft ² /s	Square feet per day			N/A	Not available in reviewed publication
gpm	Gallons per minute			Coef	Coefficient, storage (confined aquifers)
GW	Groundwater			SY	Specific yield (unconfined aquifers)
KAF	Acre-feet, in thousands			T	Transmissivity

APPENDIX B: SURVEY SUMMARY REPORT

1. In which U.S. states do you conduct the majority of your work on conjunctive use programs?

	Response Count
Texas	5
California	3
New Mexico	2
Arizona	1
Illinois	1
Rhode Island	0

2. For the conjunctive use program in which you are currently working, researching, or are most familiar, please note the general location of the program.

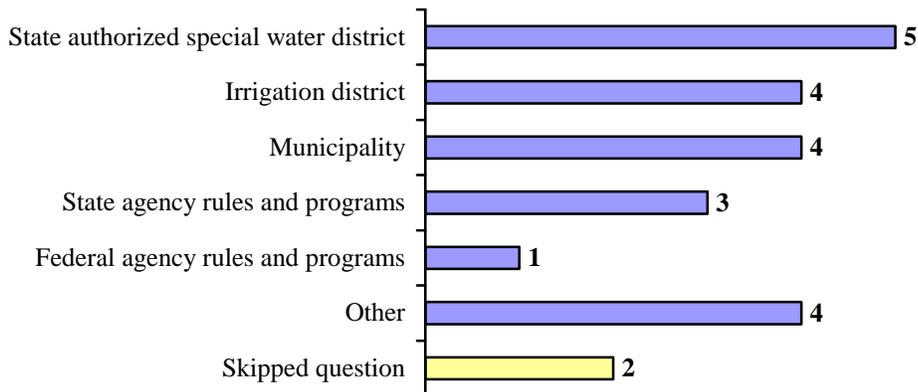
Watersheds

Lower Colorado River (TX)
 Lower Rio Grand (NM)
 Kanakee (IL)
 Big River (RI)
 Brazos River (TX)

Aquifers

Carrizo-Wilcox (TX)
 Mesilla, Jornada (NM)
 Ogallala (TX)

3. Under what entity does the conjunctive use program operate? Please check all that apply.



- 4 Please indicate all water use(s) supported by this program. For each use that you checked, please rate the water use on a scale of 1 (least water use) to 5 (greatest water use).

	Average Rating	Response Count
Agriculture/Irrigation	4.00	9
Municipal	3.70	10
Rural population	3.50	6
Environmental flows	3.29	7
Industry	2.80	5
Specific habitat flows	1.40	5
	Answered question	11
	Skipped question	2

5. Water resource programs experience various stages of development. Based on your experience, please note the approximate durations of the stages below in the conjunctive use program with which you are most familiar.

	1-12 months	1-5 years	6-10 years	11-20 years	21-50 years	>50 years	Response Count
Planning	2	3	5	1	0	0	11
Construction & implementation	1	5	2	2	0	0	10
Growth of operations	1	0	3	4	1	0	9
Phase-out	0	1	1	0	1	2	5

Answered question 11

Skipped question 2

6. In your experience, what is a general breakdown of experience and training in persons working with conjunctive use programs? Please check applicable categories and approximate number of employees.

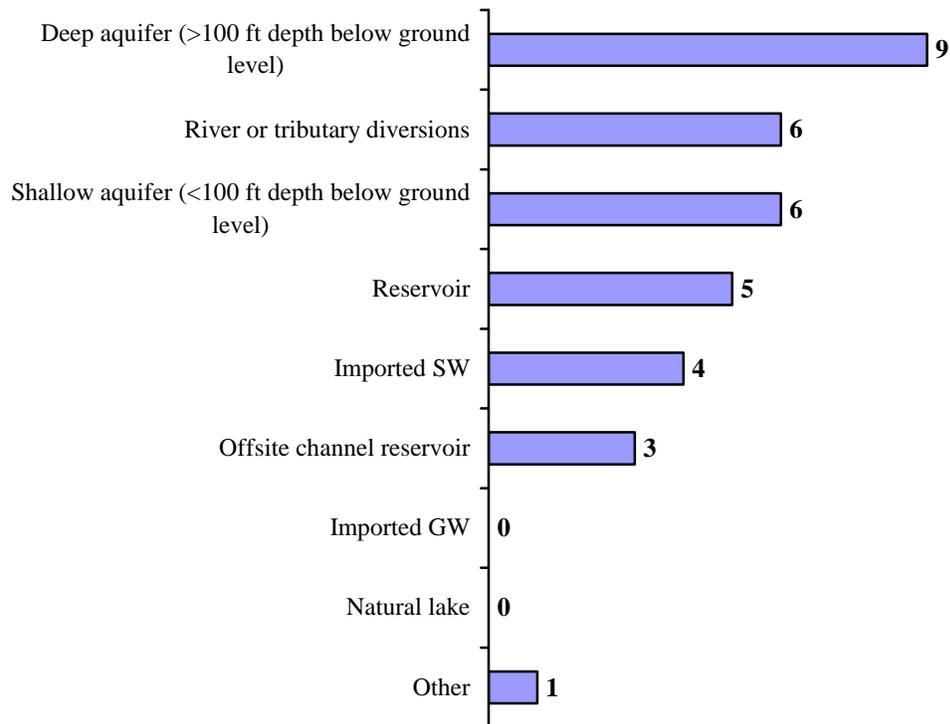
	0	1-5	6-10	11-20	21-50	>50	Unknown	Response Count
Civil Engineering	1	3	0	2	1	1	2	10
Hydrology	1	3	1	1	2	0	2	10
Hydrogeology	1	3	1	0	2	0	3	10

Law	1	3	1	1	0	0	3	9
Agricultural engineering	3	0	1	1	1	0	2	8
Soil science	2	1	0	1	1	0	3	8
Business management	0	3	1	1	0	0	3	8
Economic/financial	0	2	1	2	0	0	3	8

Answered question 10

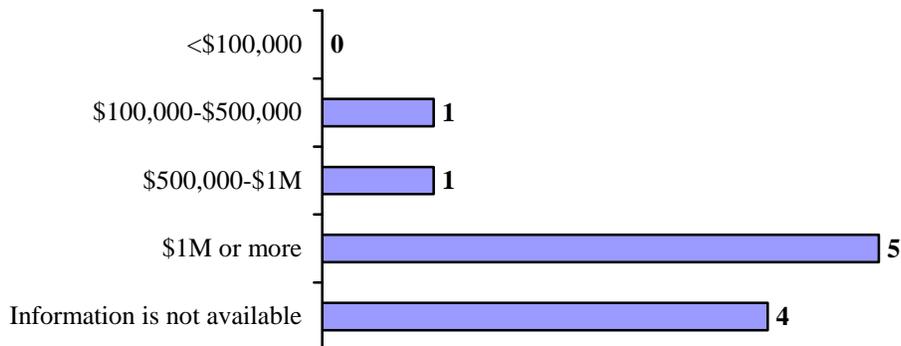
Skipped question 3

7. Do the conjunctive use programs of your experience have access or purchase rights to any of the following sources of water? Please check all that apply.



Other: treated waste-water

8. What is the approximate average yearly operating budget of the conjunctive use program with which you are most familiar (in U.S. dollars)?



9. Please help us with the demographics of the conjunctive use management by selecting the general category which best fits your expertise and background.

	Response Count
Government water agency or irrigation district	4
Research, natural resource economics	4
Research, hydrology/hydrogeology	3
Conjunctive use program manager or technical expert	1
Research, water law	1

10. What are the general physical characteristics of the surface water sources in the conjunctive use program with which you are most familiar?

	Response Count
Regional precipitation	2
Regional evapotranspiration	2
Average channel depth	2
Average channel width	2
Channel loss/gain ration (low, medium, high)	2
General flow conditions	1

11. What are the general characteristics of aquifers in the conjunctive use programs with which you are most familiar?

	Response Count
Confined or unconfined	2
General aquifer thickness	2

Average depth to water, dry seasons	2
Average depth to water, wet seasons	2
Groundwater/surface water interaction	2
Rock or sediment matrix type	1

12. How are water data monitored in your program?

	Flow gauge stations	Flow meters along distribution systems	Meters at wellheads	Datum water level measurements	Unknown	Count
Surface water sources	2	0	0	0	0	2
Groundwater sources	0	0	2	1	0	3

Answered question 3

Skipped question 10

13. With regard to water balance/availability models in the conjunctive use program with which you are familiar, please check the applicable hydraulic characteristics that are significant to the program's water balance/availability model.

	Response Count
Flow conditions (steady, unsteady state)	2
Regional precipitation data	2
Regional evapotranspiration data	2
Hydraulic conductance	2
Length of reach	1
Channel width	1
Channel scope	1
Roughness coefficient	1
Channel loss/gain estimates	1
Water quality data	0

14. Which of the following hydrogeological characteristics are most critical in the program water balance/availability model? Please check all that apply.

	Response Count
Aquifer geometry	2

Hydraulic conductivity	2
Well discharge over time	2
Storage parameters	1
Leakage parameters	1
Matrix sediments/rock type(s)	1
Water quality data	1
Spring conductance data	0
Water quality data	0
Other (please specify)	0

15. Which model software are you most likely to use for a new conjunctive use program?

	Response Count
MODFLOW with stream module	3
RiverWare	1
HEC-HMS	0
Artificial neural networks	0
DHI MIKE BASIN	0
Other (please specify)	0

16. Please define the optimization modeling approach that you have used most frequently in conjunctive use models.

Answered question 1 - Matrix-based linear programming
 Skipped question 12

17. What is the typical range of storage capacity, or volumetric flow, for the applicable surface water source(s) in the conjunctive program with which you are most familiar? Please check all that apply. [Unit: AFY = acre-feet per year]

	0-100 AFY	100-10,000 AFY	10,000-100,000 AFY	> 100,000 AFY	Response Count
River or tributary diversions	0	1	0	0	1
Imported SW	0	1	0	0	1
Reservoir	0	0	0	0	0
Natural lake	0	0	0	0	0

Offsite channel reservoir	0	0	0	0	0
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Answered question 2

Skipped question 11

18. What are typical pumping ranges for groundwater sources in the conjunctive use program? Please check all that apply. [Unit: AFY = acre-feet per year]

	< 100 AFY	100- 1,000 AFY	1,000- 10,000 AFY	10,000- 100,000 AFY	> 100,000 AFY	Response Count
Wellfields	0	1	1	0	0	2
Deep aquifer wells (>100 ft)	0	1	0	0	0	1
Shallow aquifer wells (<100 ft)	0	0	0	0	0	0

Answered question 3

Skipped question 10

19. For a change in water source, such as switching from surface water sources to groundwater, what is the primary “trigger” used by your program to define when such a change will take place?

	Response Count
Surface water volume decreases below target	1
Water prices increase above target	1
Other (response: no surface water)	1
Rainfall decreases below target	0
Groundwater levels drop below target	0
Water prices decrease below target	0

20. In your experience, what are the major benefits of conjunctive use programs? Please rate on a scale of 1-5; 1 is least beneficial, 3 is neutral, and 5 is most beneficial.

	Average Rating	Response Count
Increased water availability in region	4.17	6
Potential for drought mitigation	4.00	6

In programs with dams & reservoirs, better flood control	4.00	3
Efficient utilization of water sources and distribution systems	3.83	6
Potential for increased water conservation	3.67	6
Potential for environmental flows	3.60	5
Potential for regional water savings	3.50	2
Profits are typically greater than costs	3.00	4
In programs with irrigated agriculture, decreased likelihood of water-logged, saline fields	3.00	2
Flexibility in water prices	2.50	4
Answered question		7
Skipped question		6

21. How would you rate some of the major costs of conjunctive management programs?
1 indicates low cost impact, 3 is neutral, and 5 is high cost impact.

	Average Rating	Response Count
Conjunctive management programs are not supported by environmental groups	3.33	3
Variability in water prices contributes to financial loss	3.00	3
Cost savings difficult to realize due to institutional water price controls	2.67	3
Downstream users do not share in benefits	2.50	4
Decreased water availability	2.33	3
Groundwater sources are expensive to develop	2.33	3
Costs are greater than those of alternative water management programs	2.00	4
Answered question		4
Skipped question		9

22. Economic models for conjunctive use often focus on either water demand or water supply. In your experience, which focus is most effective over the life of a conjunctive use program and why?

Answered question 2
Skipped question 11

23. Which of these water pricing structures supports efficient water allocations in conjunctive use programs? Please check all that apply.

	Uniform rates	Block rates	Seasonal rates	Variable market rates	Response Count
Groundwater source	1	0	1	2	4
Surface water source	0	0	2	1	3
Any water source	0	0	1	2	3

Answered question 4

Skipped question 9

24. Are economic incentives (e.g., price discounts based on volume) effective in conjunctive use programs? If yes, which incentives do you consider most effective? If no, which incentives are least likely to support successful conjunctive use?

	Response Count
Yes	1
No	0

Answered question 1

Skipped question 12

25. Do price markups and rebates encourage water conservation by the water users participating in conjunctive use programs?

	Response Count
Yes	0
No	2

Answered question 2

Skipped question 11

26. In general, which surface water law best supports conjunctive use programs?

	Response Count
Prior appropriation	2

Beneficial use	1
Equitable appropriation	1
All are supportive	0
None are supportive	0
Other (please specify)	0
Answered question	2
Skipped question	11

27. Which general groundwater rule of law best supports conjunctive use programs?

	Response Count
Historic use	1
Rules of capture	0
Correlative rights	0
Restatements of torts	0
All are supportive	0
None are supportive	3
Other (please specify)	2
Answered question	6
Skipped question	7

28. If additional water permits are needed during the life of a conjunctive use program, in general how long does it take to realize a permit, beginning to end and that is not contested, in the state or region of operation in which you work?

	Response Count
0-12 months	1
1-4 years	1
5-9 years	3
10 years or more	0
Answered question	5
Skipped question	8

29. Transboundary water programs (those that cross a geographic or political boundary) may have additional considerations. Please rate the following on a scale of 1 being unimportant and 5 being very important to viable conjunctive use programs.

	Average Rating	Response Count
Physical differences in water sources	3.67	6
Geological variations in aquifers	3.60	5
Inter(river) basin transfers	3.17	6
Differences in water laws across geopolitical boundaries	2.67	6
Regional variations in water prices over time	2.60	5
Differences in user demographic across geopolitical boundaries	2.00	6
Answered question		6
Skipped question		7

30. In what manner do government institutions support conjunctive use programs?
Check all that apply within your experience.

	Federal	State	County	Muni- cipal	Irrig. Dist.	Water Dist.	Response Count
Water permitting support	0	4	0	0	0	2	6
Direct funding	0	1	2	4	1	4	5
Organizational framework	1	3	1	4	1	4	5
Taxing authority	0	3	2	2	1	3	5
Funding through grants	1	4	0	0	0	0	4
Loans	0	3	0	1	0	2	3
Answered question							6
Skipped question							7

31. For the conjunctive use program with which you are most familiar, has water availability significantly decreased in the last 10 years? For this question, a significant decrease is indicated by an average decrease over 10 years in volumetric flow available to customers.

	Response Count
Yes	3
No	4
Unknown	0
Answered question	7
Skipped question	6

32. If you answered “Yes” to the above question, what are likely causes for the decreases in available water within the conjunctive use program?

	Response Count
Regional or basinwide drought conditions	3
Declining groundwater levels	2
Declining water quality resulting in less water available for program-specific requirements	0
Change in oversight agency’s water policies	0
Volume of water use increased above program-specific projections of water use	0
Other (please specify)	2
Answered question	3
Skipped question	10

33. If the conjunctive use program with which you are familiar has experienced changes in water conservation of the users due to the program operations, what is the approximate percent increase or decrease in water conservation?

	1-5%	6-10%	>10%	NA	Response Count
Increase in water conservation	0	1	2	0	3
Decrease in water conservation	0	0	0	0	0
Unknown	1	0	0	1	2
Answered question					5
Skipped question					8

34. What are major setbacks (physical, technical, institutional, legal) to viable conjunctive use programs? Please check all that apply.

	Response Count
Differences in legal frameworks for surface water and ground water	5
Long-term (>2 years) hydrological drought conditions	2
Increasing regional population growth	2
Decentralized water agency oversight of water management programs	1
Legality of conjunctive use state rules	1
Regional decreases in groundwater levels	1
Increases in shallow groundwater/riverbank well pumping	0
Centralized water agency oversight of water management programs	0
Decreasing regional population growth	0
Other (please specify)	2
Answered question	6
Skipped question	7

35. Should conjunctive use programs be included in future federal and/or state water supply plans?

	Response Count
Yes	5
No	1
Answered question	6
Skipped question	7

36. If you answered "Yes" to the above question, what are the primary reasons that conjunctive use programs may be implemented in the future?

Response count - 4

- Reduced water availability
- Shortage of water
- Valuable, often low-cost source of "new" water
- Not a panacea but addresses a number of water supply problems

37. If you answered "No" to the question of whether conjunctive use programs should be included in water supply plans, what are reasons that conjunctive use programs might not be selected by water management agencies?

Response count - 1

- Conjunctive use is too site-specific

APPENDIX C: INTERVIEW FORMAT

**Informational Interviews, Conjunctive Use
Susan Roberts' Dissertation, 2007-2008**

Person interviewed:

Interview date:

Person's background:

Introduction:

Interview objective:

Background and Interests

- Research, water law
- Research, hydrology/groundwater
- Research, natural resource economics
- Government: _____
- Irrigation district: _____
- Conjunctive use program manager or technical expert
- Water resource industry: _____
- Other: _____

General education and experience:

Water resources interest(s):

Legal:

Research:

Government:

Lobby:

Have you worked directly with conjunctive use? Y / N

If not, what is your understanding of conjunctive use programs in TX?

Direct Conjunctive Use Knowledge / Experience

Please tell me about your experience(s) with conjunctive programs.

Location?

- N/A
- Watershed _____
- Aquifer(s) _____
- Counties _____

The program(s) operate under what legal rules (state, special district, etc)?

What water demands are listed under the conjunctive program?

- Municipal
- Agricultural / irrigation
- Industry: _____
- Indian nation
- Rural water users
- Allocations specific to environmental flows
- Other: _____

What are the program's water sources?

- River or tributary diversions
- Reservoir
- Natural lake
- Offsite channel reservoir
- Shallow aquifer (< 100-foot depth below ground level)
- Deep aquifer (> 100-foot depth below ground level)
- Imported surface water
- Imported groundwater
- Other _____

For this program, are you familiar with the program's development?

Y / N

If yes, what are the probable durations of program development?

- | | <u>< 1y</u> | <u>1-5y</u> | <u>6-10y</u> | <u>11-20y</u> | <u>21-50y</u> | <u>> 50y</u> |
|---------------------------|----------------|-------------|--------------|---------------|---------------|-----------------|
| ○ Planning | | | | | | |
| ○ Construction/operations | | | | | | |
| ○ Operations growth | | | | | | |
| ○ Phase-out | | | | | | |

In your experience, what are the background(s) you've encountered for persons working in conjunctive use? (*training, years*)

- Civil engineering ____
- Agricultural engineering _____
- Soil science _____
- Hydrology ____
- Hydrogeology ____
- Business management _____
- Law _____

- Economic / financial _____
- Other: _____

Do you have any ideas or estimations for the average annual operating budget of the conjunctive program?

- < \$100K
- \$100,000 - \$ 500,000
- \$500,000 - \$1M
- \$1M or more
- Information is not available

Models: Physical Water Information

For the conjunctive use program with which you are most familiar, which of the following channel hydraulic characteristics are most critical in the program model?

- Flow conditions
- Regional precipitation
- Regional evapotranspiration
- Channel dimensions (width, depth, slope)
- Hydraulic conductance
- Roughness coefficient
- Channel loss/gain estimates
- Water quality data

What general hydrogeologic characteristics are included in the model?

- Confined, unconfined
- Transmissivity or hydraulic conductivity
- Geologic matrix
- Average depth to water; dry vs. wet seasons
- Storage parameters
- Leakage parameters (Surface water/groundwater interaction)
- Well discharge over time
- Spring conductance data
- Water quality data

Data sources in the program?

- Flow gauge stations
- Flow meters along distribution system
- Meters at wellheads
- Datum water levels
- Unknown
- Other _____

Which model software approach is used in this program?

- HEC-HMS

- RiverWare
- Artificial neural networks
- DHI MIKE BASIN
- MODFLOW with stream module
- Other _____

Please tell me about the **optimization** modeling approach you use most frequently:

What is the typical range of storage capacity, or volumetric flow, for the applicable surface water source(s) in the conjunctive program? [0-100 acre-feet per year (afy), 100-10K, 10K-100K, >100K afy]

- River or tributary diversions
- Reservoir
- Natural lake
- Offsite channel reservoir
- Imported SW

What is the typical pumping range for wells? [same units as above]

- Well fields
- Shallow aquifer wells (< 100 feet)
- Deep aquifer wells (> 100 feet)

For a change in water source, for example when one source's availability is diminishing, or when switching from surface to groundwater, what is the primary "trigger" used by your program to define when such a change will take place?

- Surface water volume decreases below specific level
- Groundwater level drops below specific level
- Water prices decrease below specific level
- Water prices increase above specific level
- Rainfall decreases below specific level

Economics of Conjunctive Use

In your experience, what are the major benefits of conjunctive use programs?
[Open answer] _____

[Or, select from this list]

- Efficient utilization of water and distribution systems
- Decreased probability of water logged fields
- Better flood control with dams and reservoirs
- Potential for drought mitigation
- Increased water availability
- Potential for regional water savings
- Flexible water prices

- Profits are greater than costs
- Potential for increased water conservation in the region
- Potential for environmental flows

What are the major costs?

[Open answer] _____

[Or, select from this list]

- Operations are more involved than in alternative water management programs
- Groundwater sources are expensive to develop
- Decreased water availability
- Savings difficult to realize due to institutional water price controls
- Costs are greater than alternative water management programs
- Variability in water prices results in financial loss
- Downstream users do not share in benefits
- Conjunctive use not supported by environmental groups

Economic models for conjunctive use are often focused on either water demand or supply – in your experience, which approach to modeling is most effective over the life of a conjunctive program and why?

Does the program with which you are most familiar add scarcity values to water prices? If so, by what method? SW same as, or different from, GW valuation?

- Uniform
- Block rates
- Seasonal rates
- Variable market rates
- Tiered pricing
- Other _____

Are economic incentives (price discounts based on volume) effective in CU programs?

Y / N

Y: which incentives? _____

N: which incentives least likely to support CU? _____

Have you found that price markups and rebates encourage water conservation by water users?

Y / N

Legal and Institutional Considerations

In your experience, which general surface water rule of law best supports conjunctive use programs?

- Prior appropriation
- Beneficial use
- Equitable apportionment
- All of the above are supportive
- No surface water law is supportive
- Other _____

In your experience, why does this rule work best?

Which general groundwater rule of law best supports conjunctive use programs?

- Rule of capture
- Historic use
- Correlative rights
- Restatement of torts
- All of the above are supportive
- No groundwater law is supportive
- Other _____

In your experience, why does this rule work best?

If additional water permits are needed during the life of the conjunctive program, in general how long does it take to realize a permit, beginning to end, in your state or region of operation?

- 0-12 months
- 1-4 years
- 5-9 years
- 10 years or more

Transboundary water programs (geographic or political) may have additional considerations. Please rate the following, 1 unimportant to 5 very important.

- Differences in water laws across geopolitical boundaries _____
- Differences in user demographics across geopolitical boundaries _____
- Interbasin transfers _____
- Physical differences in water sources _____
- Geologic variations in aquifers _____
- Regional variations in water prices over time _____

Have you found that government agencies provide specific help to programs?

[Please specify fed, state, county, municipal, irrigation district, special water district]

- Direct funding

- Loans
- Grants
- Organizational framework for new programs
- Access to established CU programs
- Water permitting support
- Taxing authority
- Other: _____

Wrap Up

[Interviewees with no conjunctive use experience, but have particular water resource expertise)

- What changes to surface water management do you see in the near future for Texas?
- Changes to groundwater management?
 - Any discussion that you've heard about managing groundwater in the Railroad Commission approach? [centralized, but regional control for each aquifer]
- What impacts do you foresee from the \$23 billion authorization (no allocation) of the Water Resource Development Act?

[Questions for interviewees with knowledge of conjunctive use]

For the program you know best, has water availability decreased in last 10 years?
(Estimate via the average decrease in flow available to customers)

Y N Unknown

If "Yes", what are likely causes for decrease in water availability?

- Regional drought
- Declining water quality, resulting in less water
- Declining groundwater
- Change(s) in water policies
- Water use has increased above the program's original projections
- Other _____

Has the conjunctive use program with which you are most familiar observed a change in water conservation of the water users? Y / N

If yes, what is an approximate percent change?

[1-5% 6-10% > 10% change]

- Increase in water conservation
- Decrease in water conservation

- Unknown

What are major setbacks (physical, technical, institutional, legal) to successful conjunctive use programs?

- Regional decrease in rainfall
- Long-term (> 2 years) hydrologic drought conditions
- Regional decrease in groundwater levels
- Increase in shallow groundwater pumping adjacent to river
- Centralized or decentralized water agency oversight
- Increasing or decreasing population growth
- Legality of conjunctive use under state rules
- Differences in legal frameworks for surface water and groundwater
- Other _____

Should conjunctive use programs be included in future federal and/or state water supply plans? Y / N

[If “Yes”] At a minimum, what are primary reasons that conjunctive use programs may be implemented?

[If “No”] What are reasons that conjunctive use programs would not be selected by water management agencies?

VITA

Susan Vail Roberts, born in Monroe, Louisiana, completed her high school work as valedictorian of her 1977 class at St. Frederick High. She completed 2.5 years pre-med studies at Louisiana State University in Baton Rouge and a year as a medical technician at Children's Hospital in Dallas, Texas. Convinced that her life's work was with the environment, Susan finished her undergraduate studies in geological sciences at the University of Texas at Austin (1985). Based on a senior undergraduate research project in geochronology, she was awarded a research assistantship at the University of Southern California, graduating in December, 1988. Susan worked in environmental consulting from 1988 through 2002 with a focus on geology and hydrogeology investigations and remediation. Following new interests, she entered the Texas State University-San Marcos Ph.D. program in Aquatic Resources, Department of Biology.

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