Guidance Document

Part IB: Conjunctive Management of Surface and Ground Water in the Rio Grande Basin

Prepared for

U.S. Environmental Protection Agency Region VI
Geography and Water Grant

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July 16, 2010

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Summary

The Rio Grande basin of the southwestern U.S. has known, demonstrable, and complex water issues, including water shortages, flooding, non-flows along several riverbed segments, and water quality challenges. While each broad category of water issues has issues across the basin, perhaps none are as long-lasting as water supply concerns. This report and a previous report (Evaluation Report) prepared under the EPA Geography and Water grant program, focus on conjunctive management as a viable option for water supply.

The Evaluation Report provided information about conjunctive use and conjunctive management in general in addition to data and information about programs that are examples of the differential development of conjunctive management. General background information and data were also provided as a context in which to understand conjunctive management. Surveys and interviews about conjunctive management and its applicability were reported. The results strongly indicate that a clear definition of conjunctive management is the basis for understanding its potential as a water management tool.

In this document, each work task addresses the basic components of physical water systems, economic factors, legal frameworks, and a societal understanding of conjunctive water management. Physical water systems and economic factors are evaluated through in-depth assessment of published models and programs, with a resulting output of common parameters and data ranges. A review of state water laws provides insights into legal impacts on conjunctive strategies.

Research, analysis, and interviews consistently emphasize that there is no single criteria or model that sufficiently defines conjunctive management, and that its flexibility requires a broad approach rather than a single model or narrow set of data by which to rank conjunctive strategies. An in-depth evaluation of major components allows formulation of a conceptual model, criteria, and a decision matrix for planning. The framework is founded upon the four components noted above and then expanded to address critical questions about future water management approaches and issues. The conceptual model and criteria are presented as guidance and as a framework in which future programs can be designed and critiqued.

As discussed in the previous Evaluation Report, conjunctive management programs have been developed in certain areas of the Rio Grande basin. The report reviews those programs and summarizes known water management goals of conjunctive strategies, as well as geographic

locations that demonstrate water-stress characteristics that conjunctive management may suitably address. To demonstrate the applicability of the conjunctive strategy framework, the criteria and matrix are applied to the water planning region at the lower region of the Rio Grande basin.

In summary, research for this document and many other research studies and active conjunctive programs demonstrate the many strengths of conjunctive management. It can be considered a viable, cost-effective management tool, as a stand-alone and supplemental water supply approach, that is worth the consideration and detailed evaluation of many communities in the Rio Grande basin.

1.0 Introduction and Previous Report

The Rio Grande basin, 5th largest in the continental United States, is a unique watershed with varied ecosystems, ongoing water stresses, and expanding communities. Due to increased pressures on the water system, not only from water demands of growing populations but also from extreme droughts and over pumping of some aquifers, the watershed is need of focused water management options. This document reports on the results of research on conjunctive management of surface and ground waters, a water management strategy that is used and established in portions of the southwestern U.S., but not as well known in the Rio Grande basin.

The project goal is to provide well-documented research into the fundamental components that will support viable conjunctive management, regardless of water management goal or geographic location. This report, the second of two technical reports under development through the EPA Geography and Water Grant at Texas State University-San Marcos, Part IB, provides the results concerning critical factors in viable conjunctive management, and proposes a conceptual model, defines key criteria, and presents a decision matrix for application by water planning teams. The preceding Evaluation Report (Rast and Roberts, 2010) provided an overview of regional water systems, databases pertinent to conjunctive use/management in the Rio Grande Basin, selected conjunctive management programs, and the results of an online survey and interviews. This Guidance Document focuses on the evaluation of information and data from water balance and economic models and programs, legal frameworks in the three states of the basin for conjunctive management. The conjunctive strategy framework of model, criteria, and decision matrix, is applied to a location in the lower basin, with an assessment of its applicability.

A note about terminology - as the term "conjunctive use" predominates in the literature, the terminology in this report will mirror the uses in published reports. Where possible, "conjunctive use" will reference the original concept of optimizing surface and ground water sources, and "conjunctive management" will be applied to conditions that involve planning and water management strategies.

2.0 Numeric Models and Physical Parameters

Water balance models have been in use for decades, and play a significant role in planning and operating various water management strategies. A model, its inputs and assumptions appropriate to water resource goals, is part of successful water management. If a model can approximate the water system under consideration, then projections of changes in the system from variables input to the model allows different scenarios of change and projections of future outcomes. Furthermore, a water system model requires a concept of its setting and the problem being addressed. The concept is typically expressed in diagrams at a base level, separated into mathematical expressions. Software or other written code and algorithms, specific parameters, and assumptions aid in translating the concept into a working model.

Depending on the research study or water management program, a model may include optimal scenarios to formulate and realize model goals. Optimization approaches may include issues of sufficient water supply distribution, storage, and/or economic targets. In short, to optimize is to "…to make as perfect, effective, or functional as possible" (Webster 1983). In conjunctive management, optimization can be compared to a balance between data and desired targets - for example, a minimum river stage during low flow months – to outcomes of model simulations. The basis is not necessarily the algorithms used to calculate possible outcomes, but rather the optimization target. A water management team must examine whether the 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.

Regarding water balance models, the reviewed water models are termed as physical system models, water balance, numeric, or multi-objective algorithms for decision-making. The phrase "water system models" will be used herein.

2.1 Basic Characteristics of Conjunctive Water Systems

Appropriate sources of surface water or groundwater for conjunctive management are varied. 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 as a stream system can. The stream should have sufficient flow with rates measured in seconds to minutes, fairly-well defined peaks and lows, and discharge to a larger system. Typically one or more reservoirs have been created along major river stretches to provide storage and to smooth out fluctuations in the stream flow over time. Rainfall or snowmelt in the basin provides enough seasonal input to keep the system recharged. Soils and bedrock within the watershed would ideally have characteristics of sedimentation rather than high erosion rates. Natural water quality would be high, requiring little treatment prior to use, though surface water typically requires some degree of treatment prior to use.

Groundwater systems ideal for conjunctive use have different characteristics. As with surface water, flow, storage, recharge, discharge, and water quality are basic parameters of the system, but the time and geospatial scales of groundwater systems can be very different than those of stream systems. Flow and storage occur within distinct hydrogeologic strata, and in turn are affected by the subsurface layers and media, particularly as the strata may have differing characteristics within one aquifer. A stream moves through the larger landscape in a branching pattern, but an aquifer can occur in many forms. For example, groundwater may be found 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 to the 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 soils and underlying geologic strata, the quality of groundwater can be very good and require little treatment.

Other factors and interactions in the natural water system are as important as water sources. One such factor is interconnectivity between surface water and shallow groundwater. Given time, little human interference, and geographical and geological conditions, water moves across the landscape as well as infiltrating and percolating into the subsurface. If a water management strategy does not take surface and subsurface water movement 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. By treating the two systems as separate in time and space, yet connected by flow interactions, conjunctive management can include quantifiable interactions in water balance and water availability modeling.

The above descriptions give a brief overview of basic surface water and groundwater characteristics. However, this research relies on a more intensely reviewed set of information from peer-reviewed papers and programs. Such publications provide extensive information within the desired context of conjunctive management, and allow in-depth assessment of water system parameters. Evaluation of selected publications and the associated data are discussed in the following section.

2.2 Water Balance Modeling Evaluation

To better constrain how physical systems interact with the conjunctive approach, numeric models that focus on water balance budgets are analyzed in the context of conjunctive use fundamentals. The evaluation includes analysis of information pertaining to conjunctive use aspects and basic similarities and differences in parameters and data. The data sets are comprised of information, data, and results compiled from reports of selected models. Comparison of the modeling approach per project is included; that is, which models are similar and why?

Models selection is based on two criteria. First, the project or model emphasis must be on evaluation of water resources as a system towards 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.

Examination of each model's framework allows identification of parameters common and unique to a conjunctive approach. Due to development of the each modeling approach within the context of the project goals, specifications, and requirements, each model provided a set of independent data and information. To evaluate parameters associated with a conjunctive approach, parameters and data specified by the models regarding background information, surface water data, and groundwater data are compiled (see Appendix A - Tables A.1, A.2, and A.3).

Under these conditions, the peer-reviewed publications were assessed for:

- Project goal and the problem addressed through modeling
- 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
- Other factors and considerations

Reported data are analyzed as a group per common category, allowing low and high values. These parameters and data are assessed to provide a more exact framework of the conditions under which conjunctive use of water sources might best be considered for water management.

2.2.1 General Information

The reviewed papers were published in the years 1983 through 2004. The reviewed research locations in the U.S. varied, including the east coast of the U.S. (Rhode Island), the central plains of Kansas, and the west coast of California. International locations of research included the Syr Darya 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 had in common management issues of surface water and groundwater, particularly under conditions of hydraulic connectivity between surface water and groundwater. All of the areas had existing infrastructure and human water demand centers.

Project goals varied, studying questions of water use alternatives, pumping effects, tradeoffs or options resulting from different management decisions, the effects of drought, water quality degradation, decreases in storage, and environmental issues of flow targets to support salmon runs. Through compilation and a closer look at the different project goals, the variability demonstrates a fundamental strength of conjunctive management, its applicability to different geographic and water management decision conditions.

Model descriptions provided insight into variation between models. As might be anticipated, no two models were alike. Geographic, geologic, and issues-based characteristics, and the perception of which physical water source dominated the water management problems, informed the choice of model and assumptions. Surface water-centric software focused on parameters including river flow, timed reservoir releases, irrigation return flows, and groundwater base flow. Groundwater-centric software was typically a version of MODFLOW, wherein groundwater flux in and out of grid cells approximates hydraulic head changes over time (McDonald and Harbaugh, 1988). Distinguishing these fundamental modeling differences allowed recognition of the modeling predisposition towards fundamental issues of water management, perceived best approaches for modeling conjunctive use, and understanding the model's limitations and constraints on its data projections.

2.2.2 Parameters and Other Considerations

Parameters, common and unique, aid in determination of limits upon conjunctive management. Each physical system model is assessed for its water system parameters. Because some of the models noted that complete data sets were not presented, or referenced the software manuals, the list of parameters is considered reflective of conjunctive use domains, rather than a 100% complete list of all parameters that might possibly be required by any conjunctive use model. The results are shown in Table 2.1.

Common parameters include 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. These parameters, and others as required to complete input for specific models, can be expressed as numeric constants or variables. The noted common parameters are not considered a complete list, but rather a starting point for decision-makers and stakeholders interested in conjunctive water management.

Each reviewed model contains 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, and the legal / institutional impacts played important roles. Some factors such as costs were expressed quantitatively, while others were qualitative and thus more difficult to include in a model.

Striking results of the model parameter evaluation include:

- A difference was observed between the small number of parameters considered in water system models, versus large sets of parameters associated with water balance modeling and identifiable through hydrology and groundwater studies.
- Among these diverse projects, water movement and storage were common parameters. Other characteristics associated with water quality, environmental concerns, and impacts of institutional controls were site-specific, but were not necessarily specific to the conjunctive use concept.

Table 2.1 Physical System 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	<u>Incentives</u>		
Water quality	- *Taxes*		
Riverbed degradation	- *Subsidies*		
Water-logged soil	- *Water market*		
Fresh/saltwater interface			

* Numbers in parentheses denote the number of studies in which the parameter was identified.

- 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 or software-driven parameters.

2.2.3 Boundaries and Constraints

Due to the flexibility of the conjunctive approach, and its potential for application to wide-ranging locations and management goals, there are inherent difficulties in determining limits on conjunctive management. When should conjunctive management be applied, and when should it not be considered? To address this challenge, the selected model population is also evaluated for specified data ranges. The goal is 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 2.2; all data are converted to the metric system. Three tables in Appendix A show the compiled information and data as reported in their original units of measure.

Study areas ranged from 49 to 8,784 square kilometers (km^2). Precipitation was reported within a wide range, the seasonal variations contributing to water concerns. Water uses also varied, though the predominant uses were agriculture and municipal/urban. The frequency of reservoirs in the models suggests that flood control, recreation, and aesthetics may be part of the system, but not necessarily considered part of the model. Infrequently reported water uses were environmental flows and hydropower.

The annual average flow rate was commonly reported, with a low of 0 cubic meters per second (m^3/s) to a peak of 2,650 m^3/s. This range was reported in the same water system. 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 large scales of modeling, the majority of parameters were not discussed. The presence of interconnections between surface and subsurface water systems

Table 2.2 Data Ranges from 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	reported
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		5 of 12	reported
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:	22 - 80 Mm^3 / yr	89 – 160 wells	3 public supply; others are irrigation 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		9of 12	
Bedrock or fault - bounded		2 of 12	
Multi-layer aquifer system		5 of 12	

suggests that a conjunctive approach grew from problems resulting from one over-extracted water system that reflected depletion or other related problems in the tied system.

Parameters for groundwater systems tended to have more information reported and discussed than surface water-centered models. Principal groundwater flow characteristics (system recharge, hydraulic conductivity or transmissivity, storage, and pumping rates) showed great variations, which might be expected of the primarily-alluvial aquifer systems. The range of reported hydraulic conductivities (61 to 243 meters per day) was also indicative of porous, permeable formations, but not so permeable or fractured that groundwater storage was unlikely.

Ranges of total annual pumping in the modeled systems reflected the moderately hydraulic conductive and productive characteristics over time. In 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). However, in each of these studies, a consistent management concern was 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 results of the water system data evaluation:

- The varied sizes of study basins suggest that conjunctive water management is not necessarily limited by area.
- Average annual precipitation variations in the model regions indicate that tropic as well as arid regions may be suitable for conjunctive water management.
- 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 possible outcomes of the variability are 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.
- Groundwater flow parameters varied within the reviewed, primarily-alluvial, aquifer systems.

- Groundwater storage and yield was an important factor in water supply for many of the modeled systems.

In conclusion, analysis of the data ranges supports a framework for decision-making in consideration of the conjunctive concept and its application in future water management strategies, planning, and program implementation. This in-depth evaluation of models with provides information, parameters, and data ranges specific to physical water systems. While analysis of parameters in the models revealed certain common parameters, other factors and considerations of the models were extensive, indicating the variety of situations in which conjunctive management is not only applicable but also appropriate. Finally, the evaluation generated a set of data ranges for modeled water systems, useful in preparing a decision matrix towards understanding and planning conjunctive management programs (Section 5).

3.0 Economic Models and Parameters

The characteristics of conjunctive use systems are varied and changing, based on a demand-management approach; however, the economic evaluation may be based on demand or supply theories. 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. Surface water is considered replenishable, though during droughts, the volume replenished to the system can be greatly reduced and doubtful of timing. Under theoretically efficient systems, surface water allocations will allow equalization of marginal net benefits for all 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.

Economic models of water allocations can be sources of information as well as predictive analytical tools. At its foundation, an economic model may include 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.

3.1 Methods

This evaluation involves significant economic parameters of conjunctive management. Models that evaluate economic theory, and water balance models with economic applications, are analyzed for common, shared parameters. The models are also examined for unique parameters that provide insights into economically viable conjunctive management.

Based on a demonstration or proof of economic efficiency in conjunctive use, models are chosen for analysis of parameters. Certainly, more models have been published than reviewed for this research; however, selected models demonstrate significant features of economically viable, conjunctive use strategies. Some models are the first in a line of economic proofs; others build on prior models to better develop an aspect of economics in conjunctive use; and "applied" models employ economic theory in specific regions and programs of conjunctive use. Through a process of comparison, grouping, and elimination, selected models are evaluated for parameters shared by the majority of reviewed models. Economic data as provided are also examined, but found to be so specific with regard to spatial and timeframe references such that it is not possible to ascertain data ranges meaningful to general conjunctive use. Finally, through the parameter evaluation and comparison, it is possible to describe parameters unique to the success of a conjunctive use strategy.

An overview of selected models is provided in Appendix B.

3.2 Evaluation and Results

3.2.1 Common Parameters

Parameters provide a critical form of implementing the goals, targets, and approaches towards possible outcomes of modeling. Data that are input in a model have a defining role on the result. 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. Therefore, a portion of this study defines parameters common to conjunctive use models.

Common parameters are listed in Table 3.1. They are grouped as physical and economic characteristics. The common parameters are separated into characteristics distinct 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 move into the stream. 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 involved in detailed groundwater models, the reviewed economic models of conjunctive use systems 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.

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 in preparing assessing 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, along with costs of groundwater pumping at depths, energy costs, and occasionally, the cost of artificial recharge. In 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.