Development of a Conjunctive Use Management Plan for the Central Platte Valley - Task 3A: Case Studies

February, 2006

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DEVELOPMENT OF A CONJUNCTIVE USE MANAGEMENT PLAN FOR THE CENTRAL PLATTE VALLEY TASK 3A: CASE STUDIES

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1. INTRODUCTION

The Nebraska Department of Natural Resources (NDNR), Central Platte Natural Resource District (CPNRD) and Nebraska Public Power District (NPPD) are cooperatively developing a conjunctive use management plan for the surface and ground water[1] resources of the Central Platte Valley near the Platte River in Dawson and western Buffalo Counties. The initial effort is to undertake a number of tasks that have the overall objective of compiling information that will be important to the ultimate plan.

This report summarizes work done toward accomplishing Task 3A: summarizing the literature on conjunctive management programs. The emphasis is on 'case studies' -- references that present or assess the practical results of management efforts (successful or not), especially if done in the western United States. The purpose of the literature search is not to develop a comprehensive bibliography or summary of knowledge, but to compile representative references and characterize them briefly, in order to assist in the development of the work plan for Phase II of the plan. Phase II may include additional literature review, along with networking to better understand successful and less successful conjunctive use management plans in the western United States.

1.1 Literature search

The task was to be accomplished via a search of published literature, and potentially through networking discussions with agency professionals in other states.[2] Our literature search identified thousands of references, of which more than 700 are listed in Appendix A.[3] The references were identified by: a) an electronic search of on-line databases using search engines for key words such as "conjunctive management"; and b) identification of references from our library or cited in published reports.

1 We consider ground water as two words, akin to surface water. Many citations use "groundwater" and we have retained that form when quoting abstracts.

2 Networking was deferred until Phase II.

3 The Appendices were prepared using Pro-Cite software. Use of the original electronic file of the references and abstracts requires a license for this software.

In searching the literature, we looked for studies that provide results of conjunctive management efforts and/or practical advice about what works. We also sought studies that deal with water resource conditions in Nebraska and especially the Central Platte Valley, even if not directly bearing on conjunctive management. We then reviewed the references to identify those that seemed to have the greatest potential value. In most cases, our selection of a reference was based on an abstract that was available in our library or on the web.

If we decided not to include a reference it often was because the content was not relevant (much of the international literature fell into this group as did many publications on theoretical modeling and on salinity problems); in other cases the reference was put aside because it was one of many on the same subject done by the same author or set of authors, and was not among the most recent and/or the most comprehensive in the series.

We selected in excess of 100 references for more detailed consideration. For each of these references, an abstract was downloaded from the web, transcribed from the Authors' text, or written by one of the authors of this report. Our own abstracts were mostly for references considered high in importance and are typically more detailed than a conventional abstract; see for example, the abstract for Blomquist et al., 2004). In Appendix A, references for which abstracts were obtained or created are identified by an asterisk (*). In many cases our knowledge about a reference is limited to the abstract; the quality of the abstracts varied, but many were sufficient to express the central ideas relevant to the Central Platte. For several dozen references, a copy of the entire document was obtained and reviewed more closely.

Based on the results of this literature survey, we believe that information was acquired on the major topics of importance to conjunctive management, although it is certain that additional references exist that have yet to be identified, and there are definitely references that should be relevant that we have not yet acquired.[4] Indeed, in the process of final preparation of the draft version of this report, additional references were identified; an example is literature on the "HI" (Hydrology-Institutional) Model developed to address interstate allocation issues on the Arkansas River (Colorado and Kansas). The review of the material should be sufficient to guide the Phase II work plan; expanded use of the material may be appropriate during Phase II.

1.2 Types of activities represented in the literature

It is no surprise that, according to the literature, the concept of conjunctive management can take many forms and have many objectives. However, generally the concept involves either a physical or paper exchange of surface and ground water, and it most

4 An example is Glennon and Maddock, The Concept of Capture: The Hydrology and Law of Stream/Aquifer Interactions, 43 Rocky Mt. Min. L. Inst. (1997).

often trades some sort of short-term cost against a presumably larger long-term benefit, with the end objective most often being a hedge against drought and/or protection of streamflow against pumping impacts.

Conjunctive management for **physical exchange of water** typically involves the recharge of surface water into the ground water and the resulting increase in subsurface storage. The water used is surplus to immediate permitted needs, such as winter flows, flood flows, carriage flows, return flows, or wastewater.[5] The storage volume added underground is then available to be pumped during a dry season or drought period. A common approach is cyclical recharge (wet season, wet years) and pumping (dry season, droughts), and the projects that do this are often termed "aquifer storage and recovery" (ASR).

Recharge projects can have other purposes, such as to cause increased baseflow to a stream at some particularly important place or time. Colorado's recharge program to support its South Platte River obligations to Nebraska is an example. Because some baseflow is supplied by deliberate recharge, it is possible for users of ground water to pump even in situations when they otherwise would be out of priority.

While most references are for deliberate ASR efforts, some address situations in which the recharge is a coincidental outcome of a surface water irrigation project. In such cases the physical linkages exist (i.e. the surface water adds to the reserve of ground water and/or improves baseflow) but there is no deliberate effort to create a benefit from recharge. Recharge may also intentionally or coincidentally alter water quality, and sometimes for the better.

Physical exchange also can occur through means other than recharge; an example is to pump wells as a supplement to surface water supply or to augment streamflow.

Conjunctive management for **paper exchange of water** typically involves the substitution of one type of water supply for another, with the user or manager ending up with some ability to make use of additional water in the future. For example, surplus surface water may be supplied to an irrigator who then foregoes the use of ground water - in effect the ground water is left underground for future use. The net effect on the aquifer is more water in storage, just as if there had been a physical recharge project, but in this case it is accomplished by forbearance of pumping. The individual user and/or the project manager receives some right to use the saved water in the future. Water banking and "in lieu" programs are examples of this approach.

Another example is where a user of ground water has an impact on surface supplies that would not be allowed under a particular regulatory system. This user may acquire and retire an existing surface water use in order to offset the impact. New Mexico's system of water-rights management "to keep the river whole" is an example.

5 Waters that were once considered surplus may not be so considered today, especially if they are known to have environmental values.

1.3 Typical fact situation identified in the literature

There is no one standard set of issues or problems that motivate conjunctive management. However, the following fact situation that is found in much of the literature is of interest because: 1) it is common to situations for which conjunctive management has been suggested (or actually implemented); and 2) some of the characteristics are comparable to those found in the Central Platte Valley of Nebraska.

- First, a large-volume surface water irrigation use exists and is centrally managed and/or regulated. Most (seldom all) costs of the resource are passed on to users, and often these costs have increased noticeably in recent years. It is usually the case that the surface supply is vulnerable to shortages because of droughts, regulatory demands (such as the Endangered Species Act or Compact obligations) or other causes. Surface users are often looking for ways to increase the reliability and/or lower the cost of their supplies.

- Second, a large volume ground water irrigation use exists and the pumped water comes from an aquifer that is a "commons" resource, i.e. one for which there are few or no incentives for sharing. The resource is free (except for physical supply costs) and is subject to minimal regulation, especially regulation that limits pumping quantity. Indeed, use of ground water often is not even measured, especially if the use is irrigation. Users of the ground water may see no individual benefits from any effort to manage the aquifer, unless there are obvious problems from drawdowns or water quality impacts. Their motivation for participating in conjunctive management often comes from some external regulatory stimulus.

- Third, there are physical linkages between the two resources. Specifically, the surface water use usually has a benefit to the ground water use through recharge (which can replenish an aquifer and in some cases improve quality) or an adverse impact through contamination (especially if the surface water has elevated salts). The ground water use usually has a beneficial impact on the surface water through baseflow (which sustains flows in droughts) or an adverse effect through streamflow depletion. It is because of these linkages that the concept arises of managing the resources in some coordinated or conjunctive manner. More often than not, the bulk of the ground water use was developed after most of the surface water use had been established, and if there is an imbalance between benefits and adverse effects, it tends to favor the ground water users at the expense of the surface supply. It is often the case that users of the resources are not fully aware of the costs and benefits for other users.

- Fourth, there is no legal system in place that requires conjunctive management, and/or no agency with the responsibility to engage in such management. The most common situation is one in which there is some authority and centralized

management for surface water, but the management of ground water is less extensive and/or engaged in by a different entity than the surface water manager. Agencies that have responsibilities for integrated management of ground and surface waters are rare in settings where the problems above have arisen.

In this fact situation, conjunctive use and management is often suggested as a means of taking short-term actions that may come at some cost, in order that the water supply will be more sustainable and/or more reliable in the long-term. Just as surface reservoirs were built at some cost in order to improve the reliability of surface supplies, conjunctive management usually includes some use of aquifer storage as a key in the long-term management of water. The most common objectives are to physically increase water supplies, to increase supply reliability, or to improve the flexibility in supply allocation.

For convenience, we have extracted three tables from publications that provide summaries about the factors that bear on the success of conjunctive management. See Tables 1A, 1B and 1C. Note that the references from which the information was derived address projects in California and some of the findings may be specific to hydrologic or (more likely) legal conditions specific to that State.

1.4 Predicates for effective conjunctive management

The original Task 3A work plan identified three types of lessons to be learned from the case studies. Based on the literature, we combined these into two lessons and restated them as predicates or foundations for effective conjunctive management.

- There must be a legal and management structure that is capable of implementing an effective conjunctive use management program. See Section 2 of this report.

- There must be analytical tools to predict the hydrologic and other consequences of the specific measures that are proposed, and to compare these to the consequences of a future in which there is no management. See Section 3 of this report.

2. LEGAL AND MANAGEMENT STRUCTURES

2.1 Overview

Legal and management structures are the governance system under which water management takes place. The literature references that we gathered regarding legal and management structures are listed in Table 2. The abstracts for these references are provided in Appendix B.

From the literature it is clear that in the western United States, where water is generally viewed as a public resource in which there are private property rights, large-scale conjunctive use can only be accomplished if there is an adequate legal structure that defines the rights and responsibilities of all those affected by the management program. Moreover, there needs to be an efficient management entity that is capable of being effective in the implementation of the program. If multiple entities must be involved, there needs to be excellent coordination, an explicit and effective sharing of control, and substantial trust.

2.2 Key principles

There is no one model for what type of legal and management structure will work best. The following points made in the literature are those that seem most useful to those interested in conjunctive management in the Central Platte Valley.

1. A permitting program that reaches all significant users of water is an important component of the more successful conjunctive use efforts. Permits are useful because they allow for property rights in water to be defined, protected and managed through regulation and economic incentives. Management of rights that are not defined is inefficient at best and often not workable. The ideal system for defining water rights will specify rights to access, withdraw, manage, exclude, transfer and discharge to a resource. It will also have consistent rules for surface and ground water.

2. In the short-term, management will typically result in less flexibility and/or more costs to at least some individual users of water; these ideally are more than offset by benefits to the water resource as a whole, and even to the individuals over a long time frame. Because there will be real or perceived adverse effects on at least some property rights, the legal authority for conjunctive management needs to be strong, clear and sufficient to clearly assign rights, risks and responsibilities. A weak legal code virtually ensures a weak conjunctive use system.

3. The literature tends to favor market-based financial incentives over strict regulations, on the theory that the market is more flexible, more efficient, and more equitable in sharing risks. An example would be a system that begins with some legal protection of recharge, either by giving the owners of the water source certain rights to the

storage that results, or by excluding others from using the water. The market form of this system might charge a fee on those users of ground water who benefit from the recharge that comes from surface users, with the fee being earmarked to maintain the recharge. The result is both an incentive for the surface users to continue the recharge, even in a drought, and relief to them for the costs of the recharge. Fees are usually commodity based, i.e. they increase in proportion to the amount of water used, so that the user of water has an additional financial consideration when making a decision about how much water to use and how to use it.

4. Where a strong regulatory approach is taken, there is a preference for these too to have some type of market component. For example, instead of an outright moratorium on new wells, or a inflexible priority administration of water rights, a common option is to protect senior rights legally, but allow juniors to effectively access the senior rights through a regulated system which allows water rights to be acquired and transferred. This can be done privately or through a public water bank, but in either case the limited supply of water tends to move toward uses with higher economic value. Some type of public welfare provision may be among the considerations in the regulation of transfers, so as to protect social, cultural or environmental values which otherwise would not be reflected in price.

5. The literature makes clear that the more that management is centralized and at the scale of the resource (e.g. has oversight over an entire drainage basin or sub-basin), the more likely it is to be effective. Conversely, the more entities that have a role in management, and the more these operate independently, the more difficult it will be to establish a sound program.

6. It is essential to define the situation-specific objectives of conjunctive management and to design the legal code, regulatory program, market incentives and management entity accordingly. For example, if continued recharge from surface water irrigation is judged of great value to the users of ground water, then one path to success will probably be to establish some type of property right in recharge that can be protected and/or compensated for. If the objective is to protect senior water rights against depletions from junior pumping, then some type of water-rights marketplace is likely needed. More generally, the objectives are commonly defined based on the protection of all investments and property rights, but recognizing the need to adjust the market to favor actions that have the greatest benefit to the common good.

7. A commonly stated objective of management is “sustainability” or “safe yield”. We have yet to find a reference that defines either term in a way that is realistic and unambiguous.

8. The development of public support is essential if conjunctive management is to be successful, and this most often results if the need for management is evident, the benefits are clear, and the balance of costs and benefits is deemed equitable. Even if management results because of external regulatory forces, it is still important to

design the program so that it responds (as much as it can) to local perceptions about need, value and equity.

A number of other studies that are part of the Central Platte conjunctive use investigation will address specific legal and management conditions that could impact the Phase II scope of study, including recent changes to Nebraska law and external forces such as the Endangered Species Act (and Interstate Cooperative Agreement).

3. ANALYTICAL TOOLS

3.1 Overview

Analytical tools are the methodologies that those interested in conjunctive use apply in order to quantify the impacts of prospective policies and actions. The literature references that we gathered regarding analytical tools are listed in Table 3. The abstracts for these references are provided in Appendix C. Literature studies identify two broad categories of analytical tools that deal with conjunctive use: quantification and decision-support.

Quantification tools predict the change in some aspect of the water-resource system as a function of some other change (usually one that reflects a management decision). Typically this means some type of hydrologic modeling. The relationships analyzed may be within the ground water system (e.g. drawdown from pumping), within the surface water system (e.g. changes in canal delivery efficiencies), or the (especially important) inter-connections between the two systems (effects on recharge and baseflow). Some studies extend the quantification to relationships between water supply and irrigation practices, or even to economic outputs.

Decision-support tools are used to help identify the consequences of policies in ways that make it easy (or easier) to identify the “best” result. These include optimization models, which identify the result that achieves (or comes closest to achieving) a specified outcome, where that outcome is usually determined through some interpretation of public values or legal requirements. Thus some objective or set of objectives must be established (e.g. a goal of minimizing irrigation shortages; or of maximizing farm profit). Ideally, the natural conditions that impact the outcome are expressed in probability terms. Then, conditions that can vary depending upon management decisions are specified in accordance with the alternatives being assessed. Algorithms have been developed that can test various combinations of conditions and compare them as to how they perform in achieving the objectives.

Increasingly, decision-support is being done by “scenario” tools, which typically embed some type of quantification tool inside a platform that allows varied combinations of input assumptions to be simulated quickly and the outcomes displayed graphically. The “best” outcome can be identified by some type of objective weighting scheme, but more importantly, the display of how outcomes change with management decisions (or with assumptions such as the probability of drought) provide a foundation for discussions among stakeholders in the conjunctive management process so that decisions are based on judgment, not models.

3.2 Some basic principles

The subject of analytical tools is marked by a large body of work that is theoretical. Countless references consist of little more than equations that are said to represent a particular relationship, but where the analysis is conducted with hypothetical inputs. We did not identify one reference that could be said, with absolute confidence, to have definitively investigated a real-world conjunctive use system in a comprehensive and useful manner.

However, practical information is available in most of the references that were chosen for review (i.e. references that typically are less theoretical than the overall literature). A few overall principles are evident from this literature.

1. Good analytical tools are data hungry, both with respect to quantity (data requirements for the best models are massive) and quality (outputs are only as good as the inputs). A rule of thumb is that if a particular tool is not data intensive, the results are probably not going to be very useful. Conversely, the more detail (of good quality) that exists regarding the conditions being analyzed, the more likely the results of the analysis will be useful and effective.

2. Many of the relationships to be analyzed and managed in a conjunctive use program are highly dynamic, and many of these represent linkages from one area of concern to another. For example, recharge (from surface to ground water) and drainage (the other way around) can change quickly depending on regional and local conditions. In general, the ability to confidently predict responses to management actions is weakest for these dynamic linkages, or one pathway (pumping to streamflow) is better understood than the other (recharge from use of surface water). Another way of saying this is that the hydrologic interactions within a model need to have a dynamic that is representative of the real interactions; if any important part of the system is over-simplified, the results will have diminished value.

3. Even when dynamic responses are ignored, a critical issue for conjunctive management is always quantification of the water balance, especially the effects of irrigation. While recharge from canal seepage often can be quantified reasonably well, there are seldom good data on pumping of ground water, and usually no field data at all regarding the long-term recharge from irrigated (or other) lands. Thus techniques for estimating irrigation pumping and recharge tend to give results that are quite approximate. Much of the uncertainty about the outcome of conjunctive management will reflect uncertainty in this part of the water budget.

3.3 Hydrologic analyses

While many surface water models exist, the ground water model of choice is nearly always the U.S. Geological Survey 3D finite-difference model known as MODFLOW. Consequently, in assessing a modeling system for the integrated surface and ground

water systems, the first inquiry would be to identify a surface water model that can be used with MODFLOW.[6]

There are at least two other attributes (beyond MODFLOW compatibility) of a surface water model to be considered for use in analysis of conjunctive management.

1. The representation of the irrigation system should be as explicit as practical. A model that is easy to use with MODFLOW, but gives only a generalized picture of behavior in the surface system, will have little value. This is particularly important where the basis for conjunctive management is predicated on maintaining or enhancing surface supplies because of presumed benefits to ground water.

2. The model should be relatively advanced in its ability to handle the exchanges of water between the surface and subsurface systems, e.g. to calculate quantities of recharge, baseflow and phreatophyte evapotranspiration.

The STREAM package for MODFLOW is the tool of choice (versus OPSTUDY) because it provides considerable flexibility and some ability to do routing. MODSIM is an attractive alternative that provides decision-support, surface water routing, and integration with MODFLOW. The existing OPSTUDY model of the Platte system is not sufficiently dynamic for use in this project.

A tool that has been developed primarily for use in decision-support analyses is known as response functions. To generate these functions, a model such as MODFLOW is run with a unit stress (or recharge rate) input at one model cell and this is repeated for every cell. The results can usually be generalized, as by sets of curves (different sets for different areas of the model domain), such as those that show streamflow depletion in percentage of pumping rate, as a function of distance from the stream and time. The curves allow decision-support models to be run with sound hydrologic quantification input, but without the need to repeatedly rerun the MODFLOW and related surface models.

The concept of a response function is comparable to the SDF (stream depletion factor) concept of Jenkins (1968) in that it provides an easy way of quantifying the complex relationship between pumping (or recharge) and streamflow depletion, and it produces stand alone outputs -- that is, once the functions are generated they can be utilized in maps or spreadsheets without the need to repeatedly run the model. Moreover, response functions are usable in many more contexts that the SDF, and the results are considered more accurate.

One code of interest for generating response functions is MODRSP which is a GIS-based procedure that can be used in conjunction with MODFLOW.

6 The existing OPSTUDY model of the Platte River is not an ideal tool in part because it cannot be integrated with MODFLOW, in part because it is not dynamic.

3.4 Irrigation analyses

Some studies of conjunctive management have attempted to simulate the irrigation response to variations in water supply and/or management policies, and in particular to predict rates of ground water pumping as a function of surface supplies, drought conditions, regulations and policies, economic conditions and other controlling factors. CROPSIM is one example from Nebraska, and one that is useful because it outputs recharge rates. Another that deserves notice is a relatively new package for MODFLOW known as FARM. The module computes the amount of pumping that will occur as a function of the crop requirement, the availability of surface supplies, and the net economic gain from pumping, and offers policy options such as fulfilling all demands, or responding to shortages in various ways, such as deficit irrigation or stacking a water allotment on high-value crops. Net recharge, canal leakage, stream impacts and pumping are all calculated.

3.5 Decision-support

We have yet to find a study in which an optimization model was relied upon to make a major change in water supply management. At most, the literature tends to cite such models as proof of general principles, such as the value of aquifer storage compared to surface reservoir storage. Moreover, optimization models tend to embed the key algorithms in relatively unreachable forms, so that the reasons WHY a particular outcome is “best” is hard to discern.

However, this study was not done in sufficient depth to conclude that there would be no value added from optimization modeling in the Central Platte. If such modeling is done, the likely focus would be on surface water, since use of that resource typically involves more complex decisions than ground water. MODSIM provides for optimization of surface water networks, typically in the context of water allocations. For ground water optimization, the USGS has published the GWM code; also used is MODOFC, which is available free from the University of Massachusetts; MF3K-GWM is a more recent program for management of ground water. The applications of these codes we found in the literature all addressed optimization of contamination.

Among decision-support tools that focus on the quick simulation of scenarios with effective outputs, the STELLA platform is gaining widespread acceptance. Our own experience with STELLA is that it is effective in scenario building; and our expectation is that its use would be more effective in the Central Platte than any type of optimization modeling. The bottom line for all decision-support tools is their potential use in achieving public support. If the analytical tools show that the proposed legal and management structures are effective in achieving outcomes that the public recognizes as having value, then public support should follow.

Table 1A. Priority ranking of impediments to implementing a cost-effective conjunctive use water management program in California (NWRI, 1998).

	Impediment
1	Inability of local and regional water governance entities to build trust, resolve differences (internally and externally), and share control
2	Inability to match benefits and funding burdens in ways that are acceptable to all parties, including third parties
3	Lack of sufficient federal, state, and regional financial incentives to encourage groundwater conjunctive use to meet statewide water needs
4	Legal constraints impeded conjunctive use regarding: storage rights, basin judgments, area of origin, water rights, and indemnification
5	Lack of statewide leadership in the planning and development of conjunctive use programs as part of comprehensive resource planning, and recognizing regional and stakeholders' interests
6	Inability to address: quality differences in "put" vs. "take"; standards for injection, export, and reclaimed water; and unforeseeable future groundwater degradation
7	Risk that water stored cannot be extracted when needed because of infrastructure, water quality/level, politics, institution/contractual provisions
8	Lack of assurances to prevent third-party impacts and to increase willingness of local citizens to participate
9	Lack of creativity in developing lasting "win-win" conjunctive use projects, agreements, and programs
10	Supplemental suppliers and basin managers have different roles and expectations in relation to conjunctive use
11	Allocation of regional water systems' costs on the basis of annual water sales does not provide incentives to efficiently use supply
12	Inadequate understanding of water management among the California citizenry and politicians making it difficult to build a case for conjunctive use
13	Lack of understanding of the effect of recharge and extraction within the basin
14	Lack of clearly defined shortage allocation plan for imported water
15	Lack of public debate/understanding of what water as a commodity vs. as a public resources means
16	Administrative constraints within programs resulting in in-lieu recharge limitations, failure to maximize wet-year storage, and conflict in a dry-year production
17	Lack of market conditions, policies, and guidelines for wheeling water for conjunctive use
18	Lack of agreement on storage calculation methods resulting in concerns as to amount of water stored, appropriate use of incentives, value of incentives
19	Land use zoning does not adequately address water management, water contamination, and recharge issues
20	Lack of adequate surface water storage in California to provide flexibility to maximize conjunctive use programs
21	Lack of a single entity overseeing groundwater recharge/recovery operations, target aquifers, and points-of-use
22	Lack of awareness of the real expense of properly designed groundwater management and conjunctive use programs
23	TDS level of Colorado river water
24	Current uses of existing facilities may conflict with the realization of conjunctive use opportunities
25	Lack of consistent regulatory approval process
26	Long-term hydrology vs. short-term weather events and the misconception that engineering analysis can provide certainty

Table 1B. Factors in successful programs (Thomas, 2001).

FACTOR	DESCRIPTION
Character of banked water	Imported from a hydrologically disconnected source; better quality than in situ water.
Bank sited within boundaries of managing agency	Assumes agency genuinely represents the interests of affected landowners. "One of the factors most determinative of … success".
Avoiding hydrologic risks during recovery Efforts fall into three categories: 1. limits on operations to avoid adverse impacts on other groundwater users; 2. arrangements to compensate for impacts or absorb the costs on other groundwater users; 3. information systems sufficient to avoid adverse impacts.	Examples of measures to minimize hydrologic risks: • Volumetric limits: extractions limited to fixed % of banked water to account for evaporation and migration from aquifer; 90% in the CA examples. • Water table limits: example is "fifteen-foot/three-year" rule, where withdrawals don't cause GW levels to decline by over 15 ft versus what would have occurred without project over a 3-yr period. • Limits on the placement of extraction wells: so as not to impact neighboring wells; avoid interaction with stream system (unless the bank is located to increase base flows). • Limits on the timing of pumping: restrict to off-season or off-days; provide time for recharge. • Curtail pumping: stop pumping or compensate for interference with neighboring wells. • Compensation: for increased pumping costs by neighbors, with fast/easy claims processing. • Provide alternative water supplies: as an alternative to monetary compensation; or in exchange for forbearance from pumping. • Assume responsibility for deepening neighbor's wells: or restrict recovery wells to those shallower than the neighbors'. • Develop good baseline information: especially drawdown tolerances of existing wells.
Monitoring program	By independent committee, including potentially affected landowners and ground-water users, for data collection and analysis, and ability to modify plans and curtail extractions.
Avoidance of legal risks: dispute resolution procedures	Entrust to monitoring committee; or submit to binding arbitration before a registered engineer or hydrologist.
Local benefits	Cash payments; or a share of the banked water. "Successful case studies show a myriad of arrangements that are the product of negotiated agreements among the parties." "First right" can be to the banking partners, or to other entities if benefits to members are sufficient to induce voluntary participation.

Table 1B. Factors in successful programs, continued.

FACTOR	DESCRIPTION
Financial arrangements	Contractual arrangements must cover conveyance, recharge, extraction, reintegration, i.e. all operating costs. For instance, receiving payments when water is stored and extracted. Semitropic banking program cited as "essentially cost and risk free", charging $50/AF in 1998. In the Arvin-Edison program, inability to deliver ground water is countered by the ability to buy back banked water at the marginal cost of alternative supplies.
Local control	"In all successful cases analyzed, the overlying water district is in charge of the recharge and recovery operations. For agricultural water district bankers, this construct seems to work because landowners who rely on groundwater are represented in the governance of the water district." And "in most cases, the active outreach of the district's president or general manager was a key to overcoming the landowner's initial apprehension regarding a banking program".
Institutional cohesion	Need a common planning framework. Need multiple forums for communication and cooperation. Work with an umbrella agency. Private sector organizations often have more flexibility than public agencies.
Local support and public involvement	Involving local stakeholders, consistently and meaningfully, "is a common element of successful programs". Leadership by local officials is important. SNAGMA project took the time to train and educate stakeholders and used professional facilitation. The monitoring committee of the Kern Water Bank was a forum that brought in overlying users adjacent to the project.
Environmental documentation	Relatively streamlined processes for environmental documentation (state instead of federal requirements) "probably increased the likelihood of success".

Table 1C. Factors in unsuccessful programs (Thomas, 2001).

FACTOR	DESCRIPTION
Character of banked water	The case studies show that projects that rely on passive recharge (natural infiltration) "are perilous". Other problems: lack of power to curtail pumping in the event of injury to others; banking water of poorer quality than native groundwater.
Technical analyses	Public confidence can be undermined by the appearance of implementation steps done before thorough technical and environmental analyses. For the Madera Ranch project, concerns about lost water were not answered (banked water interacting with surface streams and migrating from the site, creating impacts to orchards and sensitive crops). For the State Drought Water Bank, a programmatic environmental report was perceived to be too general and without mitigation.
Time constraints	Rushed projects achieve less support and have less time for complete technical analysis. For the Madera Ranch project, the property owner's deadline may have caused such problems.
Planning and response to drought	Projects made for drought response may not work if extended to conjunctive management. Such projects lack the technical analysis (hydrologic understanding and monitoring program) needed to avoid well interference. Rather, build the drought response into the banking program, so that all necessary approvals and permits are in place. May require subsidizing.
Monitoring programs	Problems include not enough monitoring wells and lack of public access to the data. May need to make data available in real time over the internet.
Institutional arrangements and local control	Fears are that outside interests will gain control (which argues for local control). Need to mitigate third party impacts early in the process. Fears are that municipalities will have access, gain control, be codified users, and take water rights (EBMUD and Madera Ranch were examples of that fear being an issue). As an antidote, 19 counties had written anti-export ordinances "that generally prohibit exports in the absence of a permit of limited duration, issued by a local groundwater management authority". A state water code amendment reinforced the antidote. However, statutory limits may not allow for compensation as a contract would. Madera Ranch project might have worked if a stakeholder monitoring committee had been set up with enforceable operational rules. Also helpful might have been "an agreement to provide a quantity of banked water to alleviate conditions of overdraft".
Local support and public involvement	"A public interaction program, or the lack thereof, is often the sole or major reason for the failure to implement a water program." Needs to be early (conceptual stage), continuous, two-way, and transparent, utilizing local knowledge. Local opposition "was the factor that had perhaps the most significant impact on all three of the unsuccessful projects", regardless of technical merits. Points to need for public education and involvement.

Table 2. References related to legal and management structures.

State	Author/date	Subject
Multiple	Blomquist et al., 2004	Institutional policy; coordinated management
	Bryner & Purcell, 2003	Institutional policy; coordinated management
	DuMars, 2004	Prior appropriation; instream, downstream
	Fort, 1998	Case studies
	Gaul, 2002	Overview on systems
	Radosevich, 1978	Historical on water laws
	Tellman, 1996	Basic legal frameworks
	Vincent and Dempsey, 1993	Literature review by objective
	Wilhite, Donald A.	Drought and water crises
	Wrachien et al., 2002	General overview and perspective
	Young, Robert. A.	Determining the economic value of water
AZ	AZ Water Banking Auth., 2004	Ground water banking
	Blomquist et al., 2004	Institutional policy; coordinated management
	Orr and Colby, 2004	Riparian flows; case study
	Schlager, 1995	Formation of interest groups
CA	Aladjum, 2003	Coordinated management; Regulations: SW/GW
	Blomquist et al., 2004	Institutional policy; coordinated management
	Coe, 1990	Ground water banking
	Dinar & Xepapadeas, 1998	Institutional policy - NPS
	Maddock and Hardan, 1995	Banking imported water, Kern Co.
	Montgomery Watson, 2000	Banking in Southern California
	Nat. Heritage Inst., 2004	Banking in Central Valley
	Nat. Water Res. Inst., 1998	Impediments
	Purkey and Mansfield, 2002 (NHI)	Banking in Central Valley
	Pyle, 1988	Banking in Kern County
	Schuck and Green, 2003	Surfacing water pricing and well use
	Sienkeiwich, 1990	Banking imported water - incentives
	Sunding, 2000	Market-based strategies
	Thomas, 2001	Banking in Central Valley; institutional arrangements
	Thompson and Reynolds, 2002	Case study - management district
CO	Cech, 1984	District case study
	Grigg et al., 1987	Owner's association; decision models
	MacDonnell, 1988	Prior appropriation; case studies
	MacDonnell, 1989	Water quality, water rights and conjunctive use
	Simpson, 1997	Legal re KS & CO; remaining issues
	Watt et al., 2002	Managed recharge for flow augmentation
HA	Smith and Roumasset, 2001	Case study - water transport
ID	IDWR, 1999	General and case study
	IDWR, 2000	Rules for conjunctive use management
	IDWR, 2000a	Implementation strategy

Table 2. References related to legal and management structures, continued.

State	Author/date	Subject
ID	Ralston, 1984	Historical case studies; policy issues
	Tuthill and Goodwin, 1998	Decisions and decision support
KA	Kansas Water Office, 2004	Instream; case study
MN	Tsur, 1990	Conjunctive use, irrigation and salinity
NE	Aiken, 1980	Water law reform
	Aiken, 1999	Platte Cooperative Agreement
	Neb. Dept. of Nat. Resources, 2002	Background on laws; diagrams
	Strickland, 2003	Instream flow for protected species
NM	DuMars, 2004	Prior appropriation; instream, downstream
	Lieuwen, 1998	Water rights considerations
TX	Templer, 2001	Municipal; hindering issues
TVA	Duda, 1989	Conjunctive management of water quality
UT	Carpenter, 1987	District case study

Table 3. References related to analytical tools. DSS = decision support system.

State	Author/date	Subject
General	Ahlfeld, et al., 2005	GW management process for MODFLOW-2000
	Ahlfeld and Mulligan, 2000	Optimizing ground water systems; MODOFC
	Basagaoglu, 1999	Cost effectiveness of conjunctive use policies
	Belaineh et al., 1999	Linking reservoirs and stream/aquifer systems
	Jenkins, 1968	Rate/volume stream depletion by wells
	Marino, 2001	Regional water supply models
	McHugh, 2003	Determining permitting and compliance rules
	McKinney et al., 1999	Review of basin-level models
	Onta et al., 1991	3-step model: interactions, alternatives, costs
	Philbrick and Kitanidis, 1998	Surface/subsurface capabilities
	Ratkovich, 1998	Water deficiencies
	Schmidt et al., 2003, 2004	New FARM package for MODFLOW
	Silka and Kretschek, 1983	Incorporating climate into GW simulations
	Wagner, 1995	Simulation-optimization GW management methods
	Young, 2005	Non-market economic valuation methods
	Zhang et al., 1990	Modeling stream/aquifer systems
Australia	Chiew et al., 1995	Cost effectiveness of conjunctive use policies
Argentina	Correa, 1990	Short-term optimization (1 yr) model
	Menenti et al., 1992	Agricultural optimization model
Arkansas	Peralta and Peralta, 1986	Regional, sustained-yield model
	Peralta et al., 1995	Regional, sustained-yield model
California	Andrews et al., 1992	Simulating surface water distribution; KCOM
	Bergfeld, Lee G.	Investigative study of conjunctive use opportunities
	Dvorak, 2000	Operating rule effects on yield
	Hanson and Claudia, 2005	MODFLOW2000 with FARM Package
	Hathaway and Ma, 2003	MODFLOW simulations of river operations changes
	Jenkins et al., 2004	Economic-engineering optimization model
	Knapp and Olson, 1995	Ground/surface and recharge model
	Matsukawa et al., 1992	Management model, Mad River Basin
	Pulido-Velazquez et al., 2004	Potential and limitations
Colorado	Fredericks et al., 1998	DSS based on MODSIM
	Morel-Seytoux, 2001	Model evaluates augmentation plan
	Restrepo and Morel-Seytoux, 1989	Calibration study with SAMSON
England	Seymour, et al., 1998	GW recharge, flow and surface interaction
Florida	Yan and Smith, 1994	SFWMM + MODFLOW simulation
Idaho	Cosgrove and Johnson, 2004	Quantification of impacts to surface water
	Miller et al., 2003	Snake River Basin model expansion
	Shannon et al., 2000	GIS and basin flow modeling
	Stillwater, 2005	Rights and flow modeling using ModSim
Nebraska	Cannia et al., 2002	Hydrostratigraphic units for COHYST
	Carney et al., 2002	Stream depletion and COHYST
	Dappen and Colby, 2002	Land cover for COHYST
	Henszey et al., 2002	Water levels v grass response curves

Table 3. References related to analytical tools, continued.

State	Author/date	Subject
Nebraska	Krapu, 2002	Sandhill crane needs and the Platte River
	Kress et al., 2002	Surface lithology profiling
	Kress, et al., 2004	Use of continuous seismic profiling
	Landon et al., 2002	Riparian woodland evapotranspiration
	Lewis and Woodward, 2002	Describing COHYST
	Luckey et al., 2002	Ground water discharge using COHYST
	Peterson et al., 2002	COHYST construction, calibration
	Rus et al., 2002	COHYST and streambed conductivity
	Stansbury et al., 1991	DSS for water transfer evaluation
Rhode Island	Barlow et al., 2003	Stream/aquifer model for minimum streamflow effects
	Barlow and Dickerman, 2001	As above, but in a USGS paper
Texas	Watkins and McKinney, 1999	Alternative screening model
Washington	Scott et al., 2004	Forecasting climate variability

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Appendix B: Legal and Management Reference List

1. Aiken, J. D., 1980. The national water policy review and western water rights law reform: an overview. Nebraska Law Review Vol. 59, No. 2: p. 327-44, 73 refs. Nebraska Univ., Lincoln, NE.

Abstract: Although economic development has traditionally been accepted as a primary objective in the formulation of state and federal water policies, the achievement of most economic development objectives has resulted in increased public concern regarding the protection and preservation of natural resources. Inconsistent federal water policies have resulted from the enactment of federal environmental legislation which conflicts with existing reclamation, flood control, and hydroelectric power production programs. Water development programs are also being subjected to closer budgetary examinations than in the past. The proposed major objectives of a review and development of a national water resources management policy initiated by President Carter in 1977 included modification of state water laws to meet the environmental protection and water use efficiency objectives. Strong protests by the western states resulted in the elimination of this reform in state water rights laws as an explicit objective. However, several existing innovative water policies adopted by some western states may serve as models for state and federal officials searching for water policy alternatives. These include farm-level irrigation water use efficiency programs in Nebraska; groundwater mining regulations in Nebraska; minimum stream flow legislation in several western states; procedures for resolving conflicts between surface and groundwater users in Colorado; and policies for conjunctive management of groundwater and surface water in Washington and California. These water law developments are described, and their relevance to other western states is evaluated. Social, economic, and political objections to reform objectives constitute the major obstacle to water law reforms. Alternatives which accommodate development as well as reform objectives are both necessary and possible. Better integration of federal water programs is perhaps the most important water policy contribution the federal government could make at this time.

2. Aiken, J. David, 1999. Balancing Endangered Species Protection and irrigation Water Rights: The Platte River Cooperative Agreement. Vol. 3, No. 2.

Abstract: The federal Endangered Species Act (ESA) has become a major factor in western water policy decision making on rivers supporting endangered or threatened species. Proposed water projects have been scuttled because the project would interfere with endangered species protection. Restrictions in irrigation district operations and irrigator water rights have been required to protect endangered species under the ESA.

The ESA has now become a determining factor in the use and development of the Platte River. The ESA has thwarted major water project development within the basin, and a federal relicensing proceeding involving Nebraska's major hydropower and irrigation project has triggered a unique multistate-federal partnership to develop a basin-wide recovery plan for endangered species. The Platte Cooperative Agreement establishes a broader framework for resolving endangered species-water development conflicts than the frustrating case-by-case process it replaces.

Section I of this article discusses the Platte River and its development. Section II provides an overview of the Endangered Species Act, and how the ESA has been interpreted as affecting water rights in other endangered species protection conflicts. Section III reviews the Platte River water projects that have been stopped or delayed as interfering with endangered species protection. Section IV discusses the relicensing of Kingsley Dam by the Federal Energy Regulatory Commission (FERC), and how the Kingsley relicensing proceeding grew into the Cooperative Agreement. Section V discusses the Cooperative Agreement, and section VI identifies implementation challenges posed by the Cooperative Agreement, particularly regarding changes in water rights administration in the three Cooperative Agreement states.

3. Aladjem, D. R. E., 2003. California's other "dual system": coordinated management of groundwater and surface water. 49th Annual Rocky Mountain Mineral Law Institute, San Diego, CA.

Abstract: Among water lawyers, California is known for its "dual system" of surface water rights. Not being content with a system of riparian rights, like most states in the eastern United States, nor being content with a system of appropriative rights, like most states in the western United States, California determined early on that it would recognize both types of rights. Similarly, in the case of rights to groundwater, California developed a dual system. Lands overlying an aquifer have correlative rights; lands located away from an aquifer have appropriative rights. The subject of this paper is California's third "dual system": the manner in which rights to surface water and groundwater relate--or fail to relate--to each other.

4. Arizona Water Banking Authority, 2004. Annual plan of operation. http://www.awba.state.az.us/

Abstract: The Arizona Water Banking Authority (AWBA) was created to store Arizona's unused Colorado River water entitlement in western, central and southern Arizona to develop long-term storage credits to: (1) firm existing water supplies for municipal and industrial users (M&I) along the Colorado River and Central Arizona Project (CAP) M&I users during Colorado River shortages or CAP service interruptions; (2) help meet the water management objectives of the Groundwater Code; and (3) assist in the settlement of American Indian water rights claims. Changes in the AWBA's enabling legislation in 1999 authorized the AWBA to participate in other water banking activities, however, no new water banking activities are included in this annual Plan of Operation.

The AWBA's storage (or banking) of water is accomplished through the Underground Water Storage, Savings and Replenishment Act (UWS) enacted by the Arizona legislature in 1994 and administered by the Arizona Department of Water Resources (ADWR). Through this program, the AWBA stores renewable water that currently has no immediate, direct use in either underground storage (USF) or groundwater savings (GSF) facilities. A USF is a facility that allows water to physically be added to an aquifer. A GSF is a facility where the renewable water is used in place of groundwater, creating a groundwater savings. The UWS program mandates the accounting of the renewable water stored and the development of long-term storage credits. The long- term storage credits developed by the AWBA will then be utilized by the AWBA when future conditions warrant. The use of credits for the three objectives listed above may differ and is dependent on the source of funds utilized to develop them.

5. Blomquist, W., E. Schlager, and T. Heikkila, 2004. Common waters, diverging streams: linking institutions to water management in Arizona, California, and Colorado. 205 pp. Resources for the Future, Washington, DC.

Abstract: This book investigates water management in the arid American West. There are 3 parts, each with 3 chapters. Part 1, entitled Common Waters: Managing surface water and groundwater resources together, contains chapters on: Water scarcity, management, and Institutions; The promise of conjunctive water management; and Opportunities and obstacles for conjunctive management. Part 2 is entitled How Institutions Matter: Institutions and conjunctive management in California, Arizona, and Colorado. These States have one chapter each devoted to them. Part 3, entitled Institutions and policy change: analysis and recommendations, has chapters entitled: Tracing and comparing institutional effects; future directions of the diverging streams; and Shaping the future: Institutional changes to improve water management.

Although not evident from the title, this book is entirely addressed to the subject of conjunctive management.

<u>Chapter 1. Water scarcity, management, and institutions</u>. Four sources of the frequent water conflicts in the west: scarcity; variability (LW - this is what contributes to scarcity), growth in demand, recognition of nature's demands. To date the rising needs of people and crops have been met by drawing down the environmental water account. At p. 7 the Platte is cited as an example where environmental water needs are being added to a fully appropriated system, with the result being "gridlock". Hydropower and recreation are among other instream demands.

The technical aspects of conjunctive management are straightforward: "one captures, conserves and distributes surface water supplies when they are available, and stores them underground when they are surplus ... (and then) supplements surface water supplies with ground water as needed to get through peak demand periods (or) when surface water is unavailable ..." (P. 14).

NWRI, 1998, is cited as having identified 10 impediments to conjunctive management (ranked in priority order).

- an inability of local and regional water management governance entities to build trust, resolve differences both internally and externally, and share control;
- an inability to match benefits and funding burdens in ways that are acceptable to all parties, including third parties;
- a lack of sufficient federal, state, and regional financial incentives to encourage groundwater conjunctive use to meet statewide water needs;
- legal constraints regarding water rights, groundwater basin management, authority to store water underground, and authority to transport water across basin boundaries that impede conjunctive use;
- a lack of statewide leadership in the planning and development of conjunctive use programs as part of comprehensive water resources plans, while recognizing local, regional, and other stakeholders' interests;
- inability to address differences in quality among different types of water and unforeseeable future groundwater degradation;
- risks that water stored cannot be extracted when needed because of infrastructure, water quality or level, politics, and/or institutional/contractual provisions;
- a lack of assurances to address third-party impacts and to increase willing local citizen participation in conjunctive use projects;
- a lack of creativity in developing lasting "win-win" conjunctive use projects, agreements, and programs; and
- supplemental suppliers and basin managers have different roles and expectations in relation to conjunctive use.

Each of these top 10 items concerns institutional issues: the assignment of rights, risks and responsibilities; the distribution of costs and benefits; and the opportunities and disincentives for interorganizational cooperation and coordination of activities.

Institutions are more likely to benefit conjunctive management if they promote actions necessary to divert, impound, recharge, store, protect and extract water or protect those who invest in facilities or who store water now for recapture later; and further if they provide workable and fair methods for distributing the costs of a conjunctive management program among those who benefit from it. It is not sufficient to just indicate the importance of institutions, but one must also explain how they matter.

This chapter includes an introduction to the three states, especially their differences in defining water rights, recognizing pumping impacts on surface rights, and whether they have centralized or decentralized governance. Based on the descriptions provided, Colorado appears to be more similar to Nebraska than Arizona and, especially, California.

The conclusion of Chapter 1 is that those seeking conjunctive management have shaped institutions to their needs; but also that the shape of institutions is a major factor in how conjunctive management has been conducted.

<u>Chapter 2. The promise of conjunctive water management</u>. The bottom line concept of conjunctive management is to use the relative advantages of surface water and groundwater resources to offset each other's shortcomings. These advantages and shortcomings are described, e.g. surface water has lots of temporal variability and recovers quickly after a drought; ground water is steady but takes time to recover from heavy use. Groundwater provides a vast storage volume which does not

evaporate and is therefore comparatively secure; it also is often possible to locate extraction points (wells) near the point of demand. The primary adverse characteristics include energy for lifting, potential subsidence, and quality degradation. In sum: drawing down groundwater supplies during periods of diminished surface water makes sense, but is sustainable only if the groundwater supply is restored when surface water is available. What conjunctive management does is make the restoration of groundwater deliberate.

LW notes that one gap in the thinking of these authors is the notion of "surplus" surface water, e.g. that there are no consequences to the scalping of floods.

Groundwater can be stored by enhancing natural recharge processes, by artificial recharge, or indirectly by "in-lieu" practices (i.e. using surface water rather than groundwater when both are available, thus effectively retaining storage of the groundwater). The discussion of recharge processes focuses on percolation ponds or injection wells, and of stream flow or wastewater; recharge as a by-product of irrigation is not discussed here (though it does come up in subsequent chapters). In-lieu practices are operationally simple, and are sometimes encouraged by offering "surplus surface water" at a reduced or subsidized rate.

There is an extended discussion of "recent trends contributing to conjunctive management"; these include increasing competitive advantages of underground versus surface storage, the recognition of limits on groundwater overdrafts; and the availability of reuse water.

Chapter 3. Opportunities and obstacles for conjunctive management. Must have appropriate physical factors (hydrology, geology, surplus water, infrastructure) or conjunctive management is not feasible. But must also have minimal set of supportive institutional relationships such as water rights that encourage and protect conjunctive management investments; and water organizations to coordinate and implement.

Physical factors include, in effect, need for unconfined aquifers with favorable recharge, storage & recovery/production properties that co-exist with surface water supplies and don't immediately drain to a river. Institutional factors reflect need for coordination, large-scale distribution and recovery, monitoring; and especially the more completely specified water rights the better. P. 41: "With regard to conjunctive management in particular, dual or multiple water-rights systems - such as one set of rules for surface water and another for groundwater - raise substantially the costs of reaching agreements and implementing projects".

There is an extended discussion of what a "complete bundle" of rights includes: access, withdrawal, management, exclusion and transfer; and that the more complete the bundle, the more conducive to conjunctive management. With increasing completeness, the systems tend to go from those that reward consumption to those that also reward restraint, and especially those that internalize both the benefits and costs of actions. The right of exclusion is especially important, because without it, others may capture the benefits of investments (making investments less likely). Creating uniform groups is also an issue, e.g. in-lieu programs must assure every pumper that conjunctive management is in their long-term interest. On the other hand, the more complete the bundle of rights, the less flexibility may be available. Conjunctive management for priority protection will have a different focus than conjunctive management to store surplus surface water for later use.

Coordination issues are difficult because numerous organizations are typically involved and their interests (e.g. surface water users v. ground water users) are likely to diverge. Surface water users will want to minimize costs and liability of aquifer storage, while maximizing assured recovery; ground water users will want to get the best terms from surface water suppliers and keep recovery rules loose. Thus the central focus is typically to find an equitable allocation of benefits and costs.

Chapter 4. California. California's history of local districts creates institutional entrepreneurship that facilitates development of projects; but complex water rights law is a big impediment. The law needs to treat surface and ground water as essentially interchangeable (or at least not be a barrier to

this) if conjunctive management is to work; but California not only treats them differently but has different categories of ground water (e.g. underground stream flow, percolating ground water). The study found no conjunctive management projects except where there were basin-scale arrangements for governing ground water use. Conjunctive management was also motivated where surface water projects have an incentive to make good on water deliveries in dry years. Mostly see large projects, where stakes are high.

Chapter 5. Arizona. Conjunctive management developed relatively recently (1990s) and reflects the fact that water demands have been met by large surface projects and tapping of large ground water basins. It is mostly project surface surpluses (along with effluent) that supply the conjunctive projects, i.e. not native water. The key institutional event in Arizona was the 1980 act that changed access to ground water from open to limited, which especially impacted growing municipalities. The details of what happened then are summarized, but the key is that there is explicit recognition of rights to recharged water that comes from a project surplus, and in particular the development of long-term storage credits for artificially stored or in lieu ground water.

Chapter 6. Colorado. In Colorado (especially the South Platte), conjunctive management is not a storage hedge against drought, but rather is employed to allow farmers and municipalities greater access to ground water while protecting stream flows from pumping impacts. It is way of accommodating the historic increased in use of ground water that had impacts on senior surface rights that would otherwise be shorted; this includes impacts to Compact obligations to Nebraska. Projects are typically developed by irrigation districts and are designed to store surplus senior flows (typically using irrigation canals) and seep much of the water back to streams during the irrigation season, so that their member's lower cost, more reliable ground water can be used to the maximum extent. The legal and institutional evolution of this approach is complex, but effectively translates to a requirement that juniors develop a plan of augmentation or recharge in order to not be curtailed during shortage periods. The entire approach is very vulnerable to severe and prolonged shortages in surface water.

Chapter 7. Institutions and policy change: analysis and recommendations. While the differences among the States reflect physical differences to some degree, institutions are more important. This includes objectives -- Arizona and California seek to store surplus surface water, Colorado seeks to protect senior surface rights by maintaining stream flow. California and Arizona faced severe obstacles because water rights for surface and ground water uses are not commensurate, and there has been an absence of protections for recharged water. Arizona has made changes to somewhat overcome these problems, whereas in California, conjunctive management occurs only if there is some localized basin management in which the interests of surface and ground water users coincide, a marketplace environment exists, and controls can be put in place. Colorado's laws allow appropriators to act on their own. Conjunctive management is favored by institutions that recognize rights that exist in recharged water; and or provide for in lieu credits.

Chapter 8. Future directions of the diverging streams. The trends in the states are toward more conjunctive management.

Chapter 9. Shaping the future: institutional changes to improve water management. More complete specification of property rights (e.g. in ground water, in recharge) is important; without it, resolution of conflicts is difficult. This can include legal mechanisms for water banking and protection of recharge zones.

Appendix. Discusses methodology of study.

6. Bryner, G. and E. Purcell, 2003. Groundwater law sourcebook of the western United States. Natural Resources Law Center, University of Colorado School of Law, Boulder, CO.

Abstract: Discusses individual state laws and issues raised by them. Covers Arizona, California,

Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming. P. 3: "Groundwater is a classic example of a commons, where the incentives of each user to overuse the commonly shared resource results in an unsustainable level of consumption and eventual decline or loss of the resource." P. 4: Conjunctive use, allowing senior surface rights owners to pump groundwater, can result in "increasing the withdrawal of water from the hydrological system at unsustainable levels, and reduces water needed to sustain riparian habitat and in-stream wildlife." P. 6: "Most states provide for coordinated management of groundwater and surface water, especially where the two sources of water are clearly interconnected".

7. Carpenter, C. H., 1987. Conjunctive Use in Sevier River System, Utah. Journal of Irrigation and Drainage Engineering [ASCE] JIDEDH. Vol. 113, No. 1, p 131-140, 8 fig, 8 ref.

   Abstract: The Sevier Desert and Sanpete Valley are two subbasins within the Sevier River System in south-central Utah in which groundwater is extensively used in conjunction with surface water for irrigation. The conjunctive use has developed more by accident than by deliberate planning. The surface-water supply in the two areas was basically developed by 1920. Severe droughts in the early 1920s and early 1950s focused attention on groundwater development as a supplemental supply. Well construction gradually increased between the mid-1940s and 1960 in both basins until the problems of water rights and overdraft essentially halted further development. Groundwater pumpage in both the Sevier Desert and Sanpete Valley has fluctuated inversely with the available surface-water supplies and climatic conditions. Overdraft has not occurred and the sustained yield of the groundwater basins seems to have been established.

8. Cech, T. V., 1984. Conjunctive use of ground water and surface water in the South Platte River basin--a case study of the Central Colorado Water Conservancy District. P. 16-21, 12 ref. Proceedings of NWWA Western Regional Conference on Ground Water Management. San Diego, California, October 23-26, 1983. National Water Well Association, Worthington, OH.

   Abstract: The Doctrine of Prior Appropriation was adopted in the late 19th century in Colorado, allocating surface water to irrigators based on the date of their appropriation. This law created poor management of scarce water resources. The 1957 Act instituted a permitting process and laid the framework for administration of groundwater in the state. The Ground Water Management Act of 1965 regulated non-tributary groundwater and formed districts to manage groundwater within the designated basins. The Water Right Determination and Administration Act of 1969 placed irrigation wells under the priority system. In effect, the law requires all tributary irrigation wells to shut down during periods when water is needed to maintain surface water flow. Since the economy of eastern Colorado relies heavily on the 10,000 tributary irrigation wells of the South Platte River, these wells are allowed to pump only if they replace 5% of pumped water back into the river for surface irrigators. The Central Colorado Water Conservancy District formed a Ground Water Management Subdistrict in 1973 to provide a mechanism for administrating the allocation and replacement of this augmentation water so that irrigation wells could continue to pump. Six thousand acre-feet of water are acquired each year for augmentation. The district owns and leases ditch company stock, has a battery of wells that pump directly into the South Platte River, and is developing a series of small reservoirs to capture spring runoff for augmentation during low flow months.

9. Coe, J. J., 1990. Conjunctive use-advantages, constraints, and examples. Journal of Irrigation and Drainage Engineering. Vol. 116 No. 3, 427-443 pp. 7 ref.

   Abstract: Conjunctive use of surface water and ground water can usually increase yields at lower costs than more dams and reservoirs operated separately. There are three main types of conjunctive use projects: (1) stream diversions; (2) dam and reservoir only; and (3) total system. There are many advantages of groundwater storage compared with surface storage, and of conjunctive use compared to independent use. Physical, operational, financial, and institutional constraints may be encountered by the project proponents. Institutional issues may be the most difficult to resolve. Often, several governmental agencies may provide funds and have responsibilities for various features of conjunctive-use projects. Implementation is more difficult in countries where surface-water

development has historically dominated water supply project formulation. Court decisions in California have provided guidelines for conjunctive-use programs, especially in defining the rights of public agencies. Four areas in California that have experienced basin overdraft and increasing water demands, and where conjunctive-use operations have been implemented, are described.

10. Dinar, A. and A. Xepapadeas, 1998. Regulating water quantity and quality in irrigated agriculture: Learning by Investing under Asymmetric Information. Journal of Environmental Management. Vol. 54, No. 4, pp. 273-289, 37 ref.

    Abstract: An input-based incentive approach for controlling an agricultural non-point source pollution problem is developed. A regulatory agency designs a tax scheme and an investment policy to increase its informational base, in order to obtain the desirable water use and emissions for a set of agricultural producers whose individual water use and emissions cannot be observed without costly monitoring. The agency invests in order to increase observability of water use and emissions, and taxes the observed variables. Learning effects enhance the process of acquiring information about the individual producers' behavior. The optimal tax scheme and the cost minimizing monitoring program are determined.

11. Duda, A. M., 1989. Unified Management of Surface and Groundwater Quality Through Clean Water Act Authorities. Ground Water GRWAAR Vol. 27, No. 3, pp. 351-362, 6 fig, 1 tab, 29 ref.

    Abstract: The case is presented for why unified management of surface water and groundwater quality is needed. The seven-state Tennessee Valley region is used as a microcosm of the nation to illustrate why the quality of surface and subsurface waters should be conjunctively managed. Subsurface and surface water are commonly linked in basins across the nation, both hydrologically and institutionally. While groundwater was thought to provide approximately 30 percent of the nation's stream flow and up to 100 percent of stream flow during low flow seasons, hydrologists now recognize that groundwater plays a more active, responsive role in the generation of storm runoff than was previously thought. Also, surface waters serve as important sources of recharge of aquifers throughout the west and for karst, wetland, and coastal hydrogeologic settings in humid areas. Unified management of subsurface and surface water quality makes both hydrologic and institutional sense for dealing with cross-media, cross-agency linkages causing water pollution. Congressional testimony presented by the Tennessee Valley Authority (TVA) suggests that this unified water quality management can be achieved through a narrow amendment to the Clean Water Act requiring state adoption of (1) surface and subsurface water classification systems, (2) surface and subsurface numerical standards, and (3) conjunctive surface-subsurface water quality management programs. National minimum program requirements, federal funding, and federal program/facility compliance would provide leadership in creating new local/state/federal partnerships targeted to priority geographic areas. In this way, the state comprehensive program would become the hub around which the spokes of all different environmental and natural resource management (technology-based control) programs with surface water or groundwater quality implications would be integrated. This proactive water quality management approach would be less costly to the public than existing reactive approaches which have left taxpayers with a half million dollar remedial action bill for cleaning up our surface water resources.

12. DuMars, Christina Bruff, Drought and Conjunctive Management of Groundwater and Surface Water: Lessons from New Mexico, Washington and Arizona. Western Water Law & Policy Reporter January 2004: pp. 63-7.

    Abstract: This paper is in four parts:
    1. The connection between streams and ground water.
    2. New Mexico case law as reflected in two cases.
    3. Conjunctive management in other states.
    4. Problems with doctrines in New Mexico and the west.

    The paper was written by a lawyer, and so focuses on legal and management issues. Moreover, the

New Mexico concept of conjunctive management is antiquated and not really about resource optimization. This abstract looks at parts 2-4.

2. New Mexico case law as reflected in two cases. New Mexico is a prior appropriation state. So the conjunctive management issue arises when applications to drill wells occur in an aquifer/basin with prior stream rights. To protect those rights, three conditions must be met based on case law (does not include domestic household wells): measure pumpage; measure return flow; retire existing rights as necessary to offset any surface water impacts. Additional case law allows senior rights holders to switch from surface water use to ground water use if need be to preserve their priority and access to water, but only where the surface water rights holder is seeking to follow his water right to its source. Also, case law does not allow an irrigator with an earthen ditch to drill a well to recapture water which has seeped through his ditch and mingled with ground water; he can line the ditch though.

3. Conjunctive management in other states. Here the author confirms through citation of case law that Colorado, Idaho, Montana and Utah subscribe to the right of prior appropriation. The author does not discuss any management structure, as was done for New Mexico.

4. Problems with doctrines in New Mexico and the west. The author discusses three policy issues. The first is how much surface water must be retired and when? The author notes several complications, but does not provide management solutions. Complications include whether or not to provide for "in stream" flows when considering conjunctive use and water rights. Another consideration is that of downstream rights holders, such as other states or countries. Also noted are issues of where and when to allow drilling of wells, based on their impact to surface waters over time. The author notes that future administrators and populations bear the brunt of short-sighted decisions.

13. Fort, Denise D. 1998. Water in the west: challenge for the next century. Report of the Western Water Policy Review Advisory Commission.

Abstract: This is a 30-document, 3,000 page report, giving an overview of all aspects of water in the western U.S. Conjunctive use is addressed specifically at page 3-10: Storage and Conjunctive Use of Groundwater. The report cites several specific examples:

Kansas - the Dakota aquifer (guide/coordinate aquifer usage);

Utah - Weber Delta Sub-Area, east shore of Great Salt Lake (established policy of management and administration of ground water);

California - Arvin-Edison Storage District, southern San Joaquin valley (aquifer storage of surface water);

Nevada - Sierra Pacific Power Company and Carson City (seasonal/availability alteration of surface and groundwater sources);

Arizona - underground storage laws allow storage of surface supplies in aquifers using constructed spreading basins or injection wells, or more passive methods, and through groundwater conservation programs. "By this strategy, farms and irrigation districts can develop a plan to reduce their use of groundwater and, by exchange, receive surface water supplies...".

Nevada - injection of treated surface water by North Las Vegas and Las Vegas Valley Water District;

California - numerous examples of groundwater storage of project-supplied surface water by water districts for themselves and other districts, using Water Bank Authorities.

Notes that "well-managed recharge projects tend to be lower in cost than surface storage alternatives and often avoid negative environmental impacts".

14. Gaul, Steve , 2002. Memo on management of interrelated surface water and groundwater in other western states.

Abstract: Broad generalizations about management of interrelated groundwater and surface water in other states are difficult to support because the legal basis for management in each state is different and specific application of the available laws is often based upon local hydrologic and water use factors. Varying authorities are also often delegated to special purpose local districts for groundwater management and those authorities may either enable or require actions from those units of government.

If an extremely broad generalization were to be made it would be that: 1) many western states have some type of permitting or prior appropriation for groundwater, and 2) once groundwater use begins to significantly affect surface water rights that fact becomes relevant to whether new groundwater permits are granted, denied, or only granted with conditions. In those states where groundwater is part of the prior appropriation system a senior surface water user can also make a call on junior groundwater appropriators. However, what that means in practice is difficult to determine.

It appears that a number of states or districts close off permits for new wells in areas where pumping exceeds recharge. In some instances even existing wells are or may be regulated to attain some version of safe yield or managed depletion. Colorado has implemented a highly organized management system for conjunctive use. Idaho appears to be in the process of implementing a fairly sophisticated response to these issues and other states such as Oregon have rules in place that can facilitate addressing conjunctive use issues.

Notes by state on amount of irrigation from surface and ground water, and legal and management aspects. States listed in order of total irrigated acreage: California, Texas, Colorado, Kansas, Idaho, Washington, Wyoming, Oregon, Montana, Utah, Arizona, New Mexico, Oklahoma, Nevada, South Dakota, North Dakota

15. Grigg, N. S. and others, 1987. Voluntary Basinwide Water Management: South Platte River Basin, Colorado (revised). Colorado Water-Resources Research Institute Completion Report, USGS contract 14-34-0001-G831. USGS project G831-02. No. 133, p. 151, 27fig, 1 tab, 34 ref, 2 append. Colorado State University, Fort Collins.

Abstract: Demands for water in the South Platte River Basin are the most intense in Colorado and the result is increasing conflict over water use. The resulting litigation places financial burdens on water right owners and stresses the capability of the state administrative agencies to respond with water management decisions. A voluntary association of water right owners is proposed as a mechanism to increase the options of water users and reduce conflict over water use. The initiative for organizing it would be by the water right owners themselves. The South Platte Research Team believes that such an association could help achieve voluntary integrated basinwide water management. The association of water right owners would need information on management and exchange possibilities and the resulting impacts. Computer-based models can provide the information. Two hydrologic and decision models which are available at Colorado State University for this purpose are described. Other hydrologic models and economic models can also be utilized by the association. This report points out possible actions. It must be followed by discussions and debate, by demonstrations of what the models can accomplish, by organizational activity, and perhaps by new legislation. The research team plans to conduct workshops to discuss the next steps.

16. Idaho Dept. of Water Resources-a, 1999. Basin-Wide Issue 5, (Conjunctive Management General Provisions) In Re SRBA Twin Falls County Civil Case No. 39576 Sub-Case No. 91-00005; 1999 Supplemental Director's Report to the SRBA District Court.

Abstract: The Director of the Idaho Department of Water Resources (IDWR) submits this Supplemental Director's Report regarding Basin-Wide Issue 5 (Conjunctive Management General Provisions), in response to the "Amended Order Setting Deadline for IDWR to File Direct Testimony and Setting Initial Hearing on Basin-Wide Issue 5 on Remand - Conjunctive Management Snake River Basin-Wide" issued by the SRBA District Court on December 17, 1999. This report is the direct testimony of Karl J. Dreher in this matter.

The SRBA District Court has required that the following four issues be addressed in this report:

I. A precise definition of conjunctive management;

II. The basis for IDWR's generic recommendation for general provisions addressing conjunctive management;

III. The interplay between the sub-basin specific language and the general interconnection language; and

IV. An explanation of how the proposed general provisions are tailored to provide specific exceptions for each sub-basin within the overall Snake River Basin.

17. Idaho Dept. of Water Resources-b, 2000. Rule 37.03.11, Rules for Conjunctive Management of Surface and Ground Water Sources.

Abstract: The rules include, among other for legal authority and general statements of purposes and policy, the following sections.
"Responses to calls for water delivery made by the holders of senior-priority surface or ground water rights against the holders of junior-priority ground water rights within areas of the state not in organized water districts or within water districts where ground water regulation has not been included in the functions of such districts or within areas that have not been designated ground water management areas".
A section for calls "from areas having a common ground water supply in an organized water district".
"Administration of diversion and use of water within a ground water management area".
"Determining material injury and reasonableness of water diversions".
"Mitigation plans".
"Areas determined to have a common ground water supply".

18. Idaho Dept. of Water Resources-c, 2000. Basin-Wide Issue 5, (Conjunctive Management General Provisions) In Re SRBA Twin Falls County Civil Case No. 39576 Sub-Case No. 91-00005; Director's Response to Opening Briefs.

Abstract: The Director of the Idaho Department of Water Resources (IDWR) submits this response pursuant to the "Order Setting Trial Date, Final Pre-Trial Motions and Briefing Schedule for Basin-Wide Issue 5 (Conjunctive Management General Provision) and Order for Alternative Dispute Resolution -- I.R.C.P. 16" issued by the SRBA District Court on May 26, 2000, and amended on July 7, 2000. This response is IDWR's explanatory reply to the arguments raised in the opening briefs filed in subcase no. 91-00005 Basin-Wide Issue 5 and is not intended to open a new objection period.

This response does not reiterate the information presented in the 1999 Supplemental Director's Report to the SRBA District Court dated December 30, 1999. Instead, specific areas of the report are clarified and augmented to address specific issues identified in the opening briefs submitted by the parties. This report focuses on the following topics: scope of conjunctive management; purpose of the general provision; statutory authority for water management; technical limitations; and IDWR's implementation strategy for conjunctive management.

19. Kansas Water Office, 2004. Kansas Water Plan: Background information on Water Resource Management Categories - Water Management.

Abstract: The majority of ground water outside of the High Plains aquifer is alluvial ground water. Kansas manages surface and alluvial groundwater on a conjunctive use basis. A portion of the natural recharge that reaches the alluvial aquifer contributes to stream flow through baseflow. Some stream baseflow is protected through regulation and a percentage of the recharge is not available for appropriation. There is concern that many surface and alluvial ground water systems have been over appropriated. The amount of water that has been appropriated, the amount of baseflow contribution from alluvial and other aquifers, and potential corrective actions will be reviewed by an instream flow technical advisory committee which is described in the "new issues" subsection.

In many areas, sustainable yield management is already attained. When a senior water right is impaired, the owner can ask the Chief Engineer to provide relief by curtailing junior water right withdrawals. Another option to meet water needs are special management plans based on voluntary strategies to reduce water use in a subbasin. The Rattlesnake Creek subbasin is implementing a special management plan. Designation of an Intensive Groundwater Use Control Area (IGUCA) is another option that allows for flexible solutions, but when adopted has the force and function of law. An example is the Wet Walnut IGUCA which includes reduced water appropriations by all the water right holders that are junior to the impaired Cheyenne Bottoms water right, where those reductions help relieve the impairment. The solution utilized in the Wet Walnut does not cut any water right holder off completely, although the amount of reduction is weighted based on seniority.

20. Lieuwen, A. L., 1998. Water rights considerations regarding conjunctive use of surface water and groundwater in New Mexico. PROCEEDINGS: 42ND ANNUAL NEW MEXICO WATER CONFERENCE: GET YOUR WATER KICKS ON ROUTE 66; WRRI REP; New Mexico Water Resources Research Institute; New Mexico State University.

Abstract: Urban areas in New Mexico and other western states are seeking more efficient ways of meeting growing water demands with limited water supplies. Conjunctive use is a water management practice which combines dissimilar types of water resources, usually to maximize the net benefits from them over time. In fully developed conjunctive use systems, all available water sources and storage capacity, including underground storage capacity are managed to increase the yield, reliability of supply, and general efficiency of a water-supply system. Substantial literature exists on the engineering and economic aspects of conjunctive use; however, the legal feasibility of a conjunctive use system depends on the water rights administration system governing the use of surface water and groundwater. This paper examines water rights considerations of conjunctive use in New Mexico.

21. MacDonnell, L. J. a, 1988. Integrating Tributary Groundwater Development into the Prior Appropriation System: The South Platte Experience. Colorado Water Resources Research Institute, Fort Collins, Completion Report No. 148, USGS Contract No. 14-08-0001-G1214. USGS Project No. G1214-02. P. 46, 4 fig, 3 tab.

Abstract: Colorado has abundant supplies of tributary groundwater. The development of this groundwater proceeded virtually unregulated until 1965. By that time, important agricultural economies in the South Platte, Arkansas, and San Luis valleys had become highly dependent on the use of groundwater. However, because of the physical relationship between tributary groundwater and surface water, pumping of this groundwater was affecting the availability of surface flows. In 1969, Colorado enacted a number of provisions aimed at integrating appropriative rights to surface water and tributary groundwater. This law required that well pumping be regulated according to the priority system but with the important modification that junior diversions not be curtailed unless they cause material injury to senior water rights. A number of provisions such as alternate points of diversion, plans for augmentation, and substituted supplies facilitated continued use of existing wells. The experience of three organizations of well pumpers in the South Platte Valley in integrating their tributary groundwater use into the existing priority system is examined. The

Groundwater Appropriators of the South Platte (GASP), which includes about 3000 wells, operates under a legal provision allowing wells to pump so long as adequate replacement water is provided. This program is supervised by the State Engineer under the substitute supply provision and involves annual review and approval. The Fort Morgan Reservoir and Irrigation Company has obtained a water court approved plan for augmentation protecting the pumping of 90 wells on lands it serves. The Groundwater Management Subdistrict of the Central Colorado Water Conservancy District originally had sought a single plan for augmentation covering 870 wells in its area. Difficulties in developing a replacement plan for all these wells has caused the Subdistrict to reorient its approach.

22. MacDonnell, L. J. b, 1989. Water Quality and Water Rights in Colorado. Colorado Water Resources Research Institute, Fort Collins, Completion Report No.151, USGS Contract No. 14-08-0001-G1411. USGS Project No. G1411-02. P. 44, 92 notes.

Abstract: Water use and water quality are intimately related. The quality of water affects its usability. In turn, water use affects water quality. This fundamental link long has been recognized in the common law of water by the rule that one's use of water may not impair water quality to the detriment of another's use. Colorado rejected the common law riparian doctrine as a framework for allocating the right to use water and chose instead an allocation system which came to be known as the prior appropriation doctrine. However, while the allocation rules of riparianism were rejected, the fundamental protection of water quality was maintained. Now, water quality protection is based primarily on the Clean Water Act. There is considerable uncertainty as a matter of law and policy regarding the relationship between federal and state statutory water quality requirements and rights to use water under Colorado water law. This report begins with a review of early Colorado water quality law. Then the present state statutory system of water quality protection is summarized. Special attention is given to those provision of Colorado's water quality law aimed at protecting water rights. The report then addresses several specific issues which involve the relationship between water quality and water use. Finally, recommendations are made for improving Colorado's approach to integrating quality and quantity concerns.

23. Maddock, T. S. and D. L. Hardan, 1995. Conjunctive use agricultural water supply with artificial groundwater recharge. Proceedings of Conserv. 1996. Pp. 819-823. American Water Works Association, Denver, CO.

Abstract: The Rosedale-Rio Bravo Water Storage District (District) developed an artificial groundwater recharge project in 1960 to capture surplus local and imported surface waters and provide a conjunctive use water supply to a 43,000 acre area in Kern County, California. The project uses a historic Kern River overflow, the Goose Lake Slough, to recharge the underlying aquifer from which farmers, and now urban users, pump. Water supply contracts provide for delivery of water to the project from the adjacent Kern River and nearby federal and state water facilities. The water supply available to the District from these sources fluctuates widely, both seasonally and from year-to-year, depending on runoff conditions. The project is therefore designed for high flow rates to capture surplus water as it is available. The aquifer functions as a storage reservoir that provides both seasonal and long-term regulation of erratic water deliveries to meet demands. Urban encroachment has resulted in the conversion of about 6,000 acres of prime irrigated agricultural land to residential, commercial, and industrial use. This paper describes the facilities and operation of the District's conjunctive use project, its impact on groundwater conditions and the economic performance.

24. Montgomery Watson and WEF, 2000. Groundwater and Surface Water in Southern California, A Guide to Conjunctive Use. Prepared by Montgomery Watson Americas, Inc. and Water Education Foundation. Pp. 1-18. Association of Ground Water Agencies.

Abstract: This booklet provides current details on the potential to store additional vast amounts of water within the coastal groundwater basins of Southern California. It is the culmination of a two-year effort by individuals who took part in the AWRA Conjunctive Use Management Committee. Management and staff from the major Southern California groundwater basin management agencies

provided their data and assessment of the potential to store additional water in their basins. The committee compiled and evaluated the data and assessments to reach a conclusion on the total amount of groundwater storage available for conjunctive use management. The committee struggled to find agreement on the definitions of "conjunctive use" and "safe yield", as they varied for each agency.

This collaborative effort between the AGWA member agencies resulted in thick volumes of information, in far greater detail than anyone would care to read. It needed a summary report to simply explain the great potential for conjunctive use projects for greater self reliance of water resources in Southern California. Following the compilation of the various pieces of information and total conjunctive use amounts available from the AGWA member agencies, the consulting firm Montgomery Watson was hired to prepare the summary booklet. The Water Education Foundation provided financial support and important input and perspective to complete this booklet.
The study concluded there is a potential to store a total of over 21 million acre-feet of water for use in dry years. This is enough water for 35 million Californians for about 5 years. It does not include the potential for conjunctive use programs in other urban areas of Southern California. These areas are planned to be included in updates to this guide/booklet. It also does not include the amount of groundwater that is presently being used and conjunctive use programs operated in the Southern California area by the extraordinary management programs that have been developed over the last 100 years.

25. National Heritage Institute, 2004. System-wide investigation of Central Valley conjunctive water management opportunities.

Abstract: This is a PowerPoint presentation. It begins by listing characteristics and components of conjunctive use. Much of the presentation is specific to California's operations. Summary slides go through "factors for success".

From the NHI web site re “Conjunctive Management of surface and ground water in California’s Central Valley: A system-wide investigation”: NHI is developing the Conjunctive Use Project in the Central Valley of California to expand the benefits of the fixed endowment of water and to enhance its storage and delivery infrastructure to meet future water needs. Groundwater storage opportunities can be integrated into the existing surface water storage and delivery system of the Central Valley. The scenario involves re-operation of the eleven existing terminal reservoirs of the Central Valley tributaries. This re-operation will provide source water to actively recharge the groundwater banks with water that would otherwise spill for flood control. There are three ways to accomplish this recharge:

i. The storage and release regime is modified to allow the reservoirs to capture a larger fraction of the peak flow events as they move through the system. This water is then conveyed to secondary storage facilities, which are created by moving a substantial portion of the surface reservoir water into groundwater basins with currently unutilized storage capacity;

ii. In the case of full aquifers, which are most commonly found in the Sacramento Valley, native groundwater is extracted to create storage space, and is then subsequently replenished from an imported surface source; and

iii. Existing groundwater usage is substituted for surface water supplies, with recovery accomplished by reversing the arrangement. From an aquifer mass balance standpoint, this in lieu storage arrangement is indistinguishable from active recharge. These arrangements will require the consent and participation of at least four types of entities: the reservoir owner, the local groundwater management authority, the end-use beneficiaries, and the operators of the infrastructure needed to convey the water from a surface water reservoir to point of end-use. With the concurrence of these stakeholders, a project is likely to succeed in spite of the geo-hydrologic complexities and legal uncertainties. The project's future efforts will be concentrated on refining the analysis of reservoir re-operation to augment the water supplies, and to re-create peak flows sufficient to restore fluvial

processes in the downstream river channels as the water is conveyed to groundwater storage banks. This work is expected to proceed over the next two years.

26. National Water Research Institute, 1998. Conjunctive use water management program, workshop report. Pp. 166.NWRI Occasional Paper NWRI-98-02. Fountain Valley, CA. National Water Research Institute.

Abstract: Evaluates 26 impediments to implementing a cost-effective conjunctive use water management program in California. Ranks the top 10 and discusses how to overcome the impediments.

27. Nebraska Dept. of Natural Resources, 2002. Conjunctive use and management of surface water and groundwater in the State of Nebraska.

Abstract: This purpose of this paper is to provide background information on laws relevant to conjunctive use of surface and groundwater in Nebraska. Included are sections on historical background, Nebraska Water Law, Nebraska Water Law relevant to surface water groundwater relationships, state water planning and management and potential conjunctive use issues.

Includes diagrams on Process for Designating Management Areas for Integrated Management, as follows:

- NRD Designation of Management Area for Integrated Management (Option 1)
- NRD Designation of Management Area for Integrated Management-Joint NRD and DNR Action Plan (Option 2)
- NRD Designation of Management Area for Integrated Management-(Authority Limited to Disputes Over Interstate Compacts and Decrees and Other Formal State Contracts or Agreements) (Option 3)

28. Orr, Patricia and Bonnie Colby, 2004. Groundwater management institutions to protect riparian habitat. Water Resources Research. Vol. 40, W12S03, doi: 10.1029/2003 WR002741, pp. 1-9.

Abstract: Groundwater pumping affects riparian habitat when it causes the water table to drop beyond the reach of riparian plants. Riparian habitat provides services that are not directly traded in markets, as is the case with many environmental amenities. There is no direct market where one may buy or sell the mix of services provided by a riparian corridor. The objective of this article is to review groundwater management mechanisms and assess their strengths and weaknesses for preserving the ecological integrity of riparian areas threatened by groundwater pumping. Policy instruments available to those concerned with the effects of groundwater pumping on riparian areas fall into three broad categories: (1) command and control (CAC), (2) incentive-based economic instruments, and (3) cooperative/suasive strategies. The case of the San Pedro River illustrates multiple and overlapping strategies applied in an ongoing attempt to reverse accumulating damage to a riparian ecosystem. Policy makers in the United States can choose among a broad menu of policy options to protect riparian habitat from groundwater pumping. They can capitalize on the clarity of command-and-control strategies, the flexibility and less obtrusive nature of incentive-based economic strategies, and the benefits that collaborative efforts can bring in the form of mutual consideration. While collaborative problem solving and market-based instruments are important policy tools, experience indicates that a well-formulated regulatory structure to limit regional groundwater pumping is an essential component of an effective riparian protection strategy. Received 6 October 2003; accepted 28 May 2004; published 28 December 2004.

29. Pyle, S. T., 1988. Ground-Water Banking in Kern County, California. Water-Use Data for Water Resources Management. Pp. 251-260, 1 fig, 2 tab. Proceedings of a Symposium. American Water Resources Association, Bethesda; Maryland.

Abstract: Groundwater banking is an emerging water management technique that uses groundwater

storage capacity in the same manner as a surface water reservoir. Conjunctive use of surface water and groundwater is a well developed practice where both sources are available. Water and irrigation districts are able to augment water supplies by conjunctive use with recharge programs to conserve excess surface water and by installing wells to pump groundwater into canals otherwise used for distribution of surface water. These programs are operated using the groundwater storage basin as a common pool. Groundwater banking depends on similar physical practices and on the legal authority of an entity (municipality or water or irrigation district) to store a specific volume of water and to reclaim the same volume of water. Conjunctive use programs are presented as part of this study, which have been forerunners of banking as well as groundwater banking programs now in operation and plans for expansion of the banking concept.

30. Radosevich, George E., 1978. Western water laws and irrigation return flow. EPA-600/2-78-180. EPA-600/2-78-180. Ada, OK: Robert S. Kerr Environmental Research Laboratory.

Abstract: The impact of water law upon allocation and use of waters within the western United States is currently recognized as one of the major constraints to adaptation by irrigated agriculture of more efficient operation practices. This project provides a background of the law and evaluation of the potantials through water law interpretations or changes to implementing improved water management technology. Specifically, this report provides a synthesis of water laws of each of the seventeen western states, as well as providing a state-by-state account of the water quantity laws, paying particular attention to features in the laws and their administration that direct the manner of use and provide incentives or disincentives to more efficient use.

General recommendations are offered that will permit or induce more efficient and effective water management. Specific recommendations identify areas requiring additional research to renovate state water laws consistent with present and prospective policies and needs.

31. Ralston, D. R., R. R. Broadhead, and D. L. Grant, 1984. Hydrologic and Legal Assessment of Ground Water Management Alternatives for Idaho. Idaho Water Resources Research Institute, Moscow, Completion Report, USGS G839-05. 14-08-0001-G839. P. 159, 1 fig, 10 tab, 42 ref.

Abstract: A hydrologic and legal assessment was made of conjunctive management of surface and ground water resources of the upper Snake River Basin in Idaho. The report contains a hydrologic management classification of basins tributary to the upper Snake River and a legal examination of the uncertainties and complexities of conjunctive management of surface and ground water under the appropriation doctrine. Eleven basins tributary to the upper Snake River were selected for detailed study based upon existing data: Little Lost River, Big Lost River, Big Wood River-Silver Creek, Camas Prairia, Portneuf River, Michaud Flats, Rockland, Raft River, Rock Creek-Goose Creek, Salmon Falls Creek and Blue Gulch. The basins are classified based upon the following factors: (1) the ratio of annual basin discharge to total flow of the Snake River, (2) the ratio of annual consumptive pumpage to annual basin discharge, (3) the ratio of annual water yield to basin area, and (4) the distance that surface and ground water must flow before discharging into the Snake River. The legal uncertainties and complexities of conjunctive management examined include: (1) questions involving the magnitude and timing of the impact of junior tributary diversions upon supplies in the main source, both in private litigation between water users and in administrative regulation of water use: (2) selection of junior tributary diversions for closure when senior appropriators on the main source are not receiving their full supplies: (3) questions of burden of proof both in private litigation and in administrative regulation; and (4) the influence of policy objectives upon conjunctive management decisions. The study also focuses on a fundamental and difficult policy issue that may arise in a number of conjunctive management situations, namely, potential conflict between the policies of protecting senior vested rights and optimum development.

32. Schlager, Edella, State-centered Management and Local Level Recolt: The Case of Arizona Groundwater Management. Presented at "Reinventing the Commons," the fifth annual conference of the International Association for the Study of Common Property, May 24-28, 1995, Bodoe, Norway.

Abstract: Groundwater policy in the State of Arizona has experienced a fundamental transformation over the past twenty years, from state enforced open access, to state centered control and management, to local community governance of groundwater aquifers. The breakup of existing coalitions of private interests, and the creation of new coalitions produced this transformation. This paper examines the formation, structure, maintenance, and dissolution of various coalitions of interests that formed around groundwater policy. In particular, this paper examines 1) how private actors overcame collective action problems and formed coalitions to act in concert to achieve common goals, 2) the norms and conventions that actors of coalitions evolved or adopted to regularize relations among themselves to ensure that promises of mutual support were carried out, and 3) the impact of the structure and influence of these coalitions on the types of groundwater policies adopted and implemented in Arizona.

33. Schuck, E. and G. P. Green, 2003. Conserving one water source at the expense of another: the role of surface water price in adoption of wells in a conjunctive use system. International Journal of Water Resources Development Vol. 19, No. 1, p. 55-66; 22 refs., Water management and irrigated agriculture in the western United States.

Abstract: One potential side-effect of irrigation water rate reform is groundwater substitution. As surface water prices rise, irrigators may find it cheaper to rely on on-farm wells than a regional irrigation district. The impact of surface water price on well adoption in California, USA, is examined in a conjunctive use system where both surface water and groundwater are used to meet irrigator demand. Results indicate that as the price of surface water approaches 62% of the marginal cost of pumping groundwater, irrigators are more likely to have on-farm pumping capabilities. This result suggests that proposed water rate reforms by the US Bureau of Reclamation may result in irrigators substituting groundwater for surface water by adopting on-farm wells.

34. Sienkeiwich, A., 1990. Expanding Groundwater Production in Southern California. Hydraulics New York Pp. 336-342.

Abstract: The incentive to achieve greater conjunctive use in Southern California has been provided by the Metropolitan Water District of Southern California through a special pricing mechanism known as Seasonal Storage Service. Metropolitan is a wholesaler of imported water, providing about half of the region's water supply from its Colorado River Aqueduct and from its contract for water under California's State Water Project. Legal and environmental constraints on Metropolitan's imported water are requiring southern California to seek innovative and efficient approaches to water management, including expansion of the utility of groundwater basins to serve as storage reservoirs managed conjunctively with imported supplies. Metropolitan has established Seasonal Storage Service at a rate of $115 per acre-foot untreated and $135 per acre-foot treated to encourage greater groundwater production during droughts and peak demand periods. Seasonal Storage Service is normally provided during the period of October through April when unused State project water is generally available and demands are low. In lieu qualification criteria for Seasonal Storage Service requires agencies to develop extraction facilities and use those facilities to meet peak demands each May through September. During severe droughts or emergencies, Seasonal Storage Service would not be available and agencies would have the option of ordering higher priced noninterruptible water or drawing on groundwater storage reserves that would be replenished at later dates. A substantial increase in conjunctive use practices will be seen in the 1990's. Discounts provided through Metropolitan's water rate structure are providing the incentive to member agencies to utilize their groundwater resources in a more efficient manner.

35. Simpson, Hal D., 1997. Conjunctive use of surface and ground water in the Arkansas River Basin, Colorado. 15th Annual Water Law Conference, San Diego, CA, February 20-21, 1997American Bar Association, Section of Natural Resources, Energy, and Environmental Law.

Abstract: Discusses the conjunctive use of surface water and ground water in the Arkansas River Basin and how it has been impacted by the ongoing litigation between Kansas and Colorado. Discusses the basic components of the Arkansas River Compact, the post-compact well development

that led to the current litigation, a brief history of the current litigation, how Colorado has responded to the Supreme Court's initial ruling, and some of the difficult or contentious issues that remain.

36. Smith, R. B. W. and J. Roumasset, 2001. Constrained conjunctive-use for endogenously separable water markets: managing the Waihole-Waikane aqueduct. Agricultural Economics. Vol. 24, No. 1, pp. 61-71, 10 ref.

Abstract: An internal solution to an optimal control problem involving conjunctive-use of surface and groundwater may be inapplicable if water is not sufficiently fungible across space and time. This paper provides a more general solution and applies it to the problem of allocating a limited amount of water from the Ko'olau Mountains in Hawaii to two Oahu water districts separated by those mountains. The solution involves initially allocating all of the mountain water to the district supplied by groundwater but eventually allocating all of the water to the district supplied by surface water. The conditions for an internal solution hold only in the intervening years when some mountain water is allocated to each district.

37. Strickland, M. Dale, 2003. The proposed Platte River program, an effort at collaborative conservation of habitat for endangered species. Session No. 102. T61. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Geological Society of America, 2002 Denver Annual Meeting (Oct. 27-20, 2002), Colorado Convention Center, A102/104/106.

Abstract: On July 1, 1997 the states of Colorado, Nebraska, and Wyoming and the Department of the Interior (DOI) ("the parties") entered into the Cooperative Agreement for Platte River Research and Other Efforts Relating to Endangered Species Habitats along the Central Platte River, Nebraska (Cooperative Agreement). As part of the Cooperative Agreement, the parties agreed to implement a Platte River Recovery Implementation Program (Program) that builds on the Cooperative Agreement, resulting in potential improvements in habitat for four target species (interior least tern (*Sterna antillarum*), whooping crane (*Grus americana*), piping plover (*Charadrius melodus*), and pallid sturgeon (*Scaphirhynchus albus*)) listed as threatened or endangered. The Program proposes to improve habitat for the target species by reducing shortages to target flows estimated by the U.S. Fish and Wildlife Service for the Platte River in central Nebraska, and the protection and restoration of habitat, primarily in complexes along the river. The proposed Program is to be implemented incrementally with the First Increment covering 13 years. The proposed Program will use adaptive management, supported by an integrated monitoring and research effort to accomplish habitat goals for the target species. I describe the issues that led to the Cooperative Agreement and briefly describe the proposed Program, as of the date of the conference. My description will include the proposed approaches to protection and restoration of habitat for the target species, including in channel and out of channel habitat and the investigation of those approaches. I will also describe the monitoring and research plan and describe the different scales of monitoring, research, and adaptive management.

38. Sunding, D., 2000. The price of water . . . Market-based strategies are needed to cope with scarcity. California Agriculture Vol. 54, no. 2, pp. 56-58.

Abstract: Growing population and environmental concerns are increasing the demand for California's water resources. Historically, the state has dealt with shortages by expanding supply. In the coming years, new strategies will be required to allocate water among existing and emerging uses and to create additional supplies by nontraditional means. Three techniques will form the foundation of water management in the next era: water markets, water-use efficiency and active conjunctive use. Such methods establish prices for water that more accurately reflect costs, encouraging conservation and more efficient use patterns.

39. Tellman, Barbara, 1996. Why has integrated management succeeded in some states but not in others? Pp. 13-8. Water Resources Research Center, University of Arizona.

Abstract: This paper begins with a brief survey of the legal framework for groundwater and surface water management in the Western states. This is followed by some hypotheses, based on historical trends, to explain why integrated management has been adopted in some states, but not in others.

Thirteen states have some form of coordinated management to prevent harm to surface water rights holders from groundwater pumping, while five states do not. In practice, effectiveness can be limited by monitoring and enforcement problems, political pressures or inadequate funding.

40. Templer, O. W., 2001. Municipal conjunctive water use on the Texas High Plains. The Social Science Journal Vol. 38, no. 4, pp. 597-604.

Abstract: On the semiarid, water-short High Plains of West Texas, cities often make conjunctive use of water from widely dispersed sources, specifically groundwater from the dwindling Ogallala aquifer and the meager flow of streams rising in or crossing the area. Nineteen High Plains towns and cities, including Lubbock and Amarillo, receive most of their water supply from municipal water authorities which distribute surface water from Lake Meredith and the much smaller Mackenzie and White River reservoirs to a population of almost 500,000. Most of these communities continue to use preexisting groundwater reserves to improve quality or supplement their surface supply, and the Canadian River Municipal Water Authority has acquired extensive groundwater rights so that it can augment and improve the quality of water it dispenses from Lake Meredith. Although Texas water law has hindered rather than encouraged this conjunctive use, integrated water use, if not integrated water management, is widely practiced on the High Plains.

41. Thomas, Gregory A., 2001. Designing successful groundwater banking programs in the Central Valley: lessons from experience. The Natural Heritage Institute.

Abstract: This paper illuminates the institutional arrangements for improving water supply reliability for all sectors. Ground water banking comprises the largest component of the new storage envisioned. The paper illuminates arrangements to integrate groundwater storage into the existing surface water storage and delivery system of the Central Valley. Such groundwater banking projects would actively recharge the aquifer with imported foreign surface water originating from a source not hydrologically connected to the groundwater banking site.

42. Thompson, J. G. and R. Jr. Reynolds, 2002. Cultural evolution and water management in the Salinas River Valley. American Water Resources Association Journal. Vol. 38, no. 6, pp. 1661-1677.

Abstract: This article reports the findings of a case study of a major California water management district's effort to change its management approach. The following key findings and factors have influenced the Salinas basin management plan (BMP) and its progress: (1) the Salinas Valley is an economy dominated by highly sophisticated irrigated agriculture dependent on ground water; (2) a persistent pattern of agricultural overdraft of ground water has hurt growers primarily in the north end of the valley via induced saline intrusion of irrigation wells; (3) a complex set of water institutions, property and water rights, and land lease practices offer little incentive for good stewardship of land and water; and (4) the BMP approach initially may have intensified tension among growers and between growers and other water user groups. Water rules and practices in the Salinas Valley and Monterey County have evolved through a long historical process of adaptations. Therefore, any significant changes in local water use practices need to be understood in terms of cultural change, that is, changes in deeply held values, beliefs, and assumptions. We believe the BMP and the MCWRA are succeeding when evaluated from this evolutionary perspective. The fact that both still exist relatively intact testifies that they are working, albeit slowly.

43. Tsur, Y., 1990. Groundwater contamination and the management of a conjunctive ground and surface water irrigation system. Staff Paper - Department of Agricultural and Applied Economics, University of Minnesota (No. P90-61). P. 27, 23 ref.

Abstract: The paper describes a general framework for the intertemporal management of a

conjunctive ground and surface water irrigation system, taking into account salinization processes and the possibilities of aquifer or soil pollution. Policy implications are discussed and the results are compared with those that come from a model which neglects quality effects.

44. Tuthill, D. R. Goodwin P., 1998. Decision support for implementation of conjunctive management. _ Vol. 1, pp. 341-346, 8 ref. Conference Hydroinformatics '98. Proceedings of the Third International Conference on Hydroinformatics, Copenhagen, Denmark.

Abstract: An urgent matter facing water managers throughout the western United States is the need to implement conjunctive management of water rights in basins that support diversions from surface and groundwaters. The analysis procedure and logic used in the management process must be transparent to all interested parties and be defensible in administrative venues today and into the next century. Phase 1 of the process involves acquisition of information regarding: (1) water rights as determined by an adjudication process; (2) hydrogeologic impacts of groundwater pumping; (3) water quality impacts resulting from water diversions; and (4) applicable water laws including existing statutes and rules. Phase 2 consists of implementing a water distribution process which incorporates conjunctive management principles. Decision support approaches being considered for implementing Phases 1 and 2 are discussed, using the Boise River watershed in Idaho, USA, as an example. This paper presents a preliminary application of an artificial neural network to a water management situation. The artificial neural network appears to have strong potential in the decision support design.

45. Vincent, L. and P. Dempsey, 1993. Conjunctive water use for irrigation: good theory, poor practice. International Journal of Water Resources Development. Vol. 9, no. 3, pp. 227-245, 48 ref.

Abstract: Conjunctive water use is the integrated management of surface and groundwater to maximize water resources. Most systems are introducing joint use of surface and groundwater to overcome problems of poor water delivery or quality rather than systems which maximize water utility. The results of a literature review in conjunctive water use are presented. The objectives in conjunctive water use are examined with respect to three areas: (1) technical options to improve water availability and environmental management; (2) equity issues in joint use; (3) technological innovation in the use of groundwater. Institutions for promoting conjunctive water use, the hydrology of conjunctive water use and mathematical modeling in conjunctive use are reviewed. There is growing interest in conjunctive water use in irrigation management. However, most systems are introducing 'joint use' of surface and groundwater to overcome problems of poor water delivery or quality, rather than systems which actually maximize water utility. This paper summarizes the findings of a literature review on conjunctive use research, including the variable objectives behind its promotion and the hydrological and agricultural planning models experimented with. Effective promotion and subsequent sound management of conjunctive use technologies in irrigation require interaction between a broad range of institutions, including rural development and agricultural support agencies as well as water management bodies.

46. Watt, Jamey T., William E. Sanford, and John Stednick, 2002. Hydrogeologic investigation into the effects of managed recharge on water quality lower South Platte River, CO. Session No. 102. T61. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Geological Society of America, 2002 Denver Annual Meeting (Oct. 27-20, 2002), Colorado Convention Center, A102/104/106.

Abstract: In order to meet in-stream flow requirements at the Colorado-Nebraska border, managed recharge along the lower South Platte River Basin is being used as a method for flow augmentation. The site is located on the Colorado Division of Wildlife's Tamarack Ranch State Wildlife Area in northeastern Colorado. During late winter/early spring, when there is no call for water from the South Platte, approximately 20 acre-feet per day of water is pumped from the alluvial aquifer near the river into a recharge pond approximately 1 km away. The goal is to have water return to the river during low flow periods prior to snow melt runoff in order to augment in-stream flows for

endangered species in Nebraska. In this talk, we will present current findings on the areal and temporal distribution of water quality parameters (including nitrate, sulfate, alkalinity, DO, and specific conductance) within the alluvial aquifer between the recharge pond and the South Platte River. Data collected to date suggest 1) a zone of higher nitrate levels along the alluvial aquifer nearer the river; 2) the sulfate concentrations of the water pumped into the recharge pond is similar to that of the alluvial aquifer than to the river water; and 3) there appears to be a smaller contribution from the river during pumping than initially expected. In addition, we will present the preliminary results of a tracer test performed to address recharge pathways and timing. The understanding of the pathways and flow rates is important in determining the influence of the recharge water on groundwater and surface water quality, especially in light of the increasing use of flow augmentation along the length of the lower South Platte River.

47. Wrachien, D. de, C. A. Fasso, and D. de Wrachien, 2002. Conjunctive use of surface and groundwater: overview and perspective. Irrigation and Drainage. Vol. 51, no. 1, pp. 1-15.

Abstract: The world's fresh water resources are unequally distributed both in time and in space. Until recently water resource management focused on reallocating water to when and where it was required, a supply-side or fragmented approach. Nowadays there are signs that water resource availability is dwindling - due to both population growth and increased per capita water use - and ecosystems are being damaged. To face this challenge a new holistic approach is needed. This approach includes the integrated or conjunctive use of surface and groundwater resources and takes account of social, economic and environmental factors. Moreover, it recognizes the importance of water quality issues. In this context, the paper examines the main aspects and problems concerned with the planning, design, construction and management of conjunctive use of surface and subsurface water resources, along with its environmental impacts and constraints to sustainable development. The importance and role of research thrust, technology transfer, institutional strengthening, effective partnerships between governments and stakeholders, and sound financial frameworks are also examined. Finally, the challenges and benchmarks for future actions that the scientific community and planners have to face and deal with, are briefly outlined.

Appendix C. Analytical Tools Reference List

1. Ahlfeld, D. P. and others, 2005. GWM-A ground-water management process for the U.S. Geological Survey modular ground-water model (MODFLOW-2000). Open-file report 2005-1072, 124 p.

Abstract: GWM is a Ground-Water Management Process for the U.S. Geological Survey ground-water model, MODFLOW-2000. Three types of decision variables are supported by GWM: flow-rate decision variables, which are withdrawal or injection rates at well sites; external decision variables, which are sources or sinks of water that are external to the flow model and do not directly affect the state variables of the simulated ground-water system (heads, streamflows, and so forth); and binary variables, which have values of 0 or 1 and are used to define the status of flow-rate or external decision variables. Four types of constraints can be specified in a GWM formulation: upper and lower bounds on the flow-rate and external decision variables; linear summations of the three types of decision variables; hydraulic-head based constraints, including drawdowns, head differences, and head gradients; and streamflow and streamflow-depletion constraints. Three sample problems are provided to demonstrate the use of GWM for typical ground-water flow management problems.

2. Ahlfield, D. P. and A. E. Mullingan, 2000. Optimal management of flow in groundwater systems. 185 p. Academic Press, San Diego, Calif.

Abstract: In the decades ahead population increases are expected to place increased stress on water resources. A substantial portion of the world's fresh water is derived from groundwater. Optimal Hydraulic Control of Groundwater Systems will provide a practical guide for implementing mathematical and computer-based tools to aid in the management of groundwater. Drawn from the operations research literature, this book combines methods for optimization techniques to numerical models for the simulation of groundwater flow. The resulting management model provides a valuable tool for optimizing performance of groundwater systems. This volume will fill a significant gap in the technical literature on groundwater modeling and management.

*Provides a thorough description of the mathematics underlying the method and a step-by-step introduction to practical application,

*Introduces key concepts using an example continued throughout the book,

*Contains MODOFC software package and associated documentation that implements many of the methods described in the book,

*Details advanced topics, including nonlinear and integer problem elements and interpretation of management model results,

*Each chapter ends with a summary of selected references and brief histories of the methodologies presented in the book.

3. Andrews, E. S., F. I. Chung, and J. R. Lund, 1992. Multilayered, priority-based simulation of conjunctive facilities. Journal of Water Resources Planning and Management. Vol. 118 (1), 32-53 pp.; 30 ref.

Abstract: A network flow programming-based model, KCOM (Kern conveyance operations model), was developed to simulate water allocation and distribution in the surface water system of Kern County, California, USA. The model will help in the planning of the proposed Kern Water Bank conjunctive-use project. KCOM incorporates recharge and pumping features to allow simulation of both surface and subsurface water distribution. The water allocation capabilities of network flow programming-based simulation were enhanced in KCOM by the development of a sequential flow allocation technique, in which sources were allocated in different layers to meet only demands with authorized access to those sources. A validation simulation demonstrated the model's capabilities,

and sensitivity analysis underscored the need for improvement of the data used to describe the system. Recommendations are made for the improvement of KCOM.

4. Barlow, P. M., D. P. Ahlfeld, and D. C. Dickerman, 2003. Conjunctive-Management Models for Sustained Yield of Stream-Aquifer Systems. Journal of Water Resources Planning and Management. Vol. 129, No. 1, p. 35-48.

   Abstract: Conjunctive-management models that couple numerical simulation with linear optimization were developed to evaluate trade-offs between groundwater withdrawals and stream flow depletions for alluvial-valley stream-aquifer systems representative of those of the northeastern United States. A conjunctive-management model developed for a hypothetical stream-aquifer system was used to assess the effect of interannual hydrologic variability on minimum monthly stream flow requirements. The conjunctive-management model was applied to the Hunt-Annaquatucket-Pettaquamscutt stream-aquifer system of central Rhode Island. Results show that it is possible to increase the amount of current withdrawal from the aquifer by as much as 50% by modifying current withdrawal schedules, modifying the number and configuration of wells in the supply-well network, or allowing increased stream flow depletion in the Annaquatucket and Pettaquamscutt rivers. Alternatively, it is possible to reduce current rates of stream flow depletion in the Hunt River by as much as 35% during the summer, but such reductions would result in smaller increases in groundwater withdrawals.

5. Barlow, P. M. and D.C. Dickerman, 2001. Numerical-simulation and conjunctive-management models of the Hunt-Annaquatucket-Pettaquscutt stream-aquifer system, Rhode Island. U.S. Geological Survey Professional Paper. No. 1636, 88 p.

   Numerical-simulation and optimization techniques were used to evaluate alternatives for the conjunctive management of ground- and surface-water resources of the Hunt-Annaquatucket-Pettaquamscutt stream-aquifer system in central Rhode Island. Ground-water withdrawals from the Hunt-Annaquatucket-Pettaquamscutt aquifer exceeded 8 million gallons per day during months of peak water use during 1993-98, and additional withdrawals have been proposed to meet growing demands from within and outside of the system boundary. The system is defined by the Hunt-Annaquatucket-Pettaquamscutt aquifer, which is composed of glacial stratified deposits, and the network of rivers, brooks, and ponds that overlie and are in hydraulic connection with the aquifer. Nearly all of the water withdrawn, however, is derived from depletions of flow in the rivers, brooks, and ponds that overlie the aquifer. Streamflow depletions are of concern to environmental agencies because of the adverse effects that reductions in streamflow can have on aquatic and riparian ecosystems.

   A conjunctive-management model of the stream-aquifer system was developed to simultaneously address the water-demand and streamflow-depletion issues. The objective of the model was to maximize total ground-water withdrawal from the aquifer during July, August, and September. These three months are generally the time of year when water-supply demands are largest and streamflows are simultaneously lowest. Total withdrawal from the aquifer was limited by a set of constraints specified in the model. These constraints were (1) maximum rates of streamflow depletion in the Hunt, Annaquatucket, and Pettaquamscutt Rivers; (2) minimum monthly water demands of each of three water-supply systems that withdraw water from the aquifer; and (3) minimum and maximum withdrawal rates at each supply well.

   The conjunctive-management model was formulated mathematically as a linear program. The model was solved by a response-matrix technique that incorporates the results of transient, numerical simulation of the stream-aquifer system into the constraint set of the linear program. The basis of the technique was the assumption that streamflow-depletion rates in each river were a linear function of ground-water-withdrawal rates at each well. This assumption was shown to be valid for the conditions evaluated in this study, primarily because of the very high transmissivity of the aquifer near many of the wells pumped for water supply. A transient, numerical model of the system was developed to simulate an average annual cycle of monthly withdrawal and hydrologic conditions

representative of the 56-year period 1941-96. The transient model was used to generate characteristic streamflow-depletion responses in each river to simulated withdrawals at each well; these characteristic responses, or response coefficients, were then incorporated directly into the streamflow-depletion constraints of the linear program.

Four sets of applications of the conjunctive-management model were made to determine whether total ground-water withdrawal from the aquifer during July, August, and September could be increased over the current total withdrawal for alternative definitions of the maximum rates of streamflow depletion allowed in the Hunt, Annaquatucket, and Pettaquamscutt Rivers. Current conditions were defined as the average monthly withdrawal rates at each supply well, water demands of each of the three water-supply systems, and estimated streamflow-depletion rates during the 6-year period 1993-98. Total withdrawal from all wells in the system from July through September during 1993-98 was 506.5 million gallons. Estimated streamflow-depletion rates for 1993-98 were calculated by use of the transient model, with the 1993-98 average monthly withdrawal rates specified at each supply well. Streamflow-depletion rates calculated for July, August, and September averaged 25 percent of the model-calculated pre-withdrawal streamflow rates for the Hunt River, 19 percent for the Annaquatucket River, and 7 percent for the Pettaquamscutt River.

The first set of applications of the model were made with the current estimated rates of streamflow depletion in the Hunt, Annaquatucket, and Pettaquamscutt Rivers. Results of these applications indicated that total withdrawal from the aquifer during July, August, and September could be increased from about 8 to 18 percent (from 546.0 to 596.3 million gallons) over the current total withdrawal. The increased withdrawal would require modifications to the current annual withdrawal schedule of each supply well and, for the 18-percent increase, a modified network of supply wells that would include two new wells in the Annaquatucket River Basin. A second set of model applications then was made to determine if current estimated rates of streamflow depletion in the Hunt River could be reduced without increasing current estimated rates of streamflow depletion in the Annaquatucket or Pettaquamscutt Rivers. Decreases in the current rates of streamflow depletion in the Hunt River would result in increased streamflow in the river during these three months. Results showed that current rates of streamflow depletion in the Hunt River during July, August, and September could be decreased from 5 to 15 percent, depending on whether the existing or modified well network was used.

Subsequent model applications indicated that substantial increases in total ground-water withdrawal from the aquifer are possible, but would require increased rates of streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers. Maximum increases in the July through September withdrawal from the aquifer of about 39 to 50 percent (from 705.1 to 760.3 million gallons) over the current total withdrawal were calculated when streamflow-depletion rates in the Annaquatucket and Pettaquamscutt Rivers were allowed to increase from current estimated rates to a maximum of 25 percent of the model-calculated pre-withdrawal streamflow for each river during July, August, and September. Alternatively, it was shown that current estimated rates of streamflow depletion in the Hunt River during July, August, and September could be reduced by as much as 35 percent for the maximum allowed increases in streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers; maximum increased withdrawal from the aquifer, however, would range from 8 to 18 percent over the current total withdrawal for the 35-percent reduction in streamflow-depletion rates in the Hunt River.

Results of the different applications of the model demonstrate the usefulness of coupling numerical-simulation and optimization techniques for regional-scale evaluation of water-resource management alternatives. The results of the evaluation must be viewed, however, within the limitations of the quality of data available for the Hunt-Annaquatucket-Pettaquamscutt stream-aquifer system and representation of the system by a simulation model. An additional limitation of the analysis was the use of an average annual cycle of monthly withdrawal and hydrologic conditions. Ground-water withdrawal strategies may need to be modified to meet streamflow-depletion constraints during extreme hydrologic events, such as droughts.

Contributing areas and sources of water to the supply wells also were delineated by use of a steady-state model of the stream-aquifer system. The model was developed to simulate long-term-average ground-water flow and ground-water/ surface-water interactions in the system during the 56-year period 1941-96. Sources of water to the wells consisted of precipitation and wastewater recharge to the aquifer, streamflow leakage from natural stream-channel losses, streamflow leakage caused by induced infiltration, and lateral ground-water inflow from till and bedrock upland areas.

6. Basagaoglu, H., M. A. Marino, and R. H. Shumway, 1999. Delta-form approximating problem for a conjunctive water resource management model. Advances in Water Resources. Vol. 23, No. 1, p. 69-81.

   Abstract: A nonlinear coupled simulation and optimization model is formulated to find the optimal operating policies with a minimal cost for the conjunctive management of hydraulically interacting surface and ground water supplies. The term representing the pumpage cost in the objective function of the management model causes nonlinearity that cannot be put in a quadratic form as in the traditional approach, since drawdown in that term is a function of well pumpage and other parameters. To eliminate the nonlinearity, delta-form approximating model is formulated with a particular emphasis on the concave function of the transformed objective function. The original problem in a nonlinear form is solved by coupling the solver with a random number generator to provide the model with a different initial guess each time. However, the delta-form approximating problem is formulated as a linear mixed integer programming model. Optimal operating policies and the operation costs obtained from both models are found to be in good agreement.

7. Belaineh, G., R. C. Peralta, and T. C. Hughes, 1999. Simulation/optimization modeling for water resources management. Journal of Water Resources Planning and Management. Vol. , No 3, p. 154-161, 32 refs.

   Abstract: There is a need for enhanced linking of reservoir and stream/aquifer systems in conjunctive water management models. A simulation/optimization model was presented that integrates linear reservoir decision rules, detailed simulations of stream/aquifer system flows, conjunctive use of surface and groundwater, and delivery via branching canals to water users. The linear decision rule is an example of a rule that has been widely discussed in reservoir operation literature and is simple to program. State variables, including aquifer hydraulic head, stream flow, and surface water/aquifer interflow, were represented through discretized convolution integrals and influence coefficients. Reservoir storage and branching canal flows and interflows were represented using embedded continuity equations. Results of model application to a hypothetical study area under several scenarios show that the more detail used to represent the physical system, the better the conjunctive management. The most detailed representation provides 13% more water than the least detailed system.

8. Cannia, James C. and others, 2002. Construction of hydrostratigraphic units for the Nebraska cooperative hydrology study (COHYST) groundwater flow models. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Colorado Convention Center, A/102/104/106, Denver Annual Meeting (Oct. 27-20, 2002), Session No. 102. T61. Geological Society of America.

   Abstract: The Nebraska Cooperative Hydrology Study (COHYST) area covers 29,300 square miles in central and western Nebraska. The main products of COHYST are groundwater-flow models that can be used to analyze the effects of water-management activities proposed under the Three-State Cooperative Agreement among Nebraska, Wyoming, Colorado, and U.S. Fish and Wildlife Service. Hydrostratigraphic units are a critical input to the groundwater-flow models. The hydrostratigraphic units are based on geologic units and their associated hydraulic properties. Ten hydrostratigraphic units, eight within the High Plains aquifer and two beneath it, were based on textural descriptions of the formation characteristics and estimates of hydraulic properties. The geologic units within the High Plains aquifer in Nebraska include Quaternary-age deposits and the Tertiary-age Ogallala Group, Arikaree Group, and fractured Brule Formation. The units beneath the High Plains aquifer

include the Tertiary-age White River Group and Undifferentiated Cretaceous-age sediments. These units are meant to be used for regional model purposes and may not be appropriate for specific local characterizations. The hydrostratigraphic units were constructed with a Geographic Information System using available literature, test-hole logs, registered-well logs, observation-well logs, and surficial geologic maps. All available registered well information was put into a database, reviewed, and over 3,800 wells were selected for use in creating the units. These were added to about 2,000 test-hole logs and 340 observation-well logs. A digital coverage of available surficial geologic maps for the area was created. Additional work to refine the hydrostratigraphic units includes new test-hole drilling, shallow seismic surveys, and resistivity surveys. By using this combination of subsurface and surficial geologic information, the regional hydrostratigraphic units were completed, for use in the groundwater-flow models.

9. Carney, Clint P. and others, 2002. A comparison between stream depletion lines computed with groundwater-flow models and a classic analytical method for the Nebraska cooperative hydrology study. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Colorado Convention Center, A102/104/106, Denver Annual Meeting (Oct. 27-20, 2002), Session No. 102. T61. Geological Society of America.

   Abstract: One of the primary uses for the Nebraska Cooperative Hydrology Study (COHYST) groundwater-flow models is to aid regulators, resource managers, and groundwater developers in assessing the interaction of surface water and groundwater in the Platte River Basin. Of particular importance is the influence of new and existing pumping wells on river flows. “Stream depletion” refers to either direct removal of water from a stream or indirect capture of aquifer water flowing to the stream by pumping wells. The stream depletion factor (sdf) is a concept developed by C.T. Jenkins (1968) that has been widely used in groundwater/surface-water management. This technique determines stream depletion using analytical techniques. The sdf has units of time and indicates when the volume of stream depletion equals 28% of the volume removed by a pumping well. To compute the location of the analytical 28% depletion sdf line, only aquifer transmissivity, specific yield, and distance to the stream are needed, but the method assumes a highly idealized system. However, this approach does not address variable geologic and hydrogeologic characteristics nor boundary conditions other than a straight stream. Alternatively, the line of 28% depletion by volume can be determined with a numerical groundwater-flow model, which accounts for real-world, complex hydrologic, geologic and boundary conditions. Preliminary, single-layer COHYST models with variable, distributed parameters and 1 square-mile cells were used to determine the 40-year depletion lines for the Platte River in the central COHYST area. The simulated well location was adjusted until the line of 28% depletion could be determined. The preliminary model indicated that the stream depletion line ranged from 0.8 miles to 16.5 miles from the Platte River in the area tested. The model lines were compared to sdf lines produced in a 1982 study (Missouri Basin States Association). On the south side of the river, the model-produced lines are similar to the earlier study, with the largest deviation less than 5 miles. North of the river, greater distances between the lines estimated by the two methods existed, with the largest deviations being nearly 7 miles near where the model accounted for a tributary that probably was not accounted for in the previous study.

10. Chiew, F. H. S. and others, 1995. Technical and economic evaluation of the conjunctive use of surface and groundwater in the Campaspe Valley, north-central Victoria, Australia. Water Resources Management. Vol. 9, No. 4, p. 251-275.

    Abstract: This paper describes a technical and feasibility study of increasing groundwater usage to supplement surface water use in the Campaspe Valley in south-eastern Australia. An integrated model which simulates the surface and groundwater processes, as well as the interactions between the processes, is used to determine the sustainable long-term groundwater pumping yields. The model also provides estimates of groundwater fluxes for various management options of increasing groundwater usage. These estimates are used to assist an economic analysis to determine the relative merits of various options for the conjunctive use of surface and groundwater resources. The pumping costs, value of water and tangible salinity benefits from lowering high water-tables and reducing salt

load are considered in the economic analysis. The methodology is also relevant for other studies looking into the conjunctive use of surface and groundwater resources throughout the Murray Basin and elsewhere.

11. Correa, N. R., 1990. Optimal, operation strategies for a system with conjunctive water use. In Simonovic, S. P. et al. (Eds.) Water resource systems application. p. 482-491. Conference Water Resource Systems Application: Proceedings of the International Symposium on Water Resource Systems Application, Held in Winnipeg, Canada, June 12-15, 1990. Department of Civil Engineering, University of Manitoba.

    Abstract: A simulation-optimization approach to search optimal short-term (one hydrological year) operation strategies for a water resources system with conjunctive water use in San Juan, Argentina is discussed. The topics presented are the regulation concept for the management of the system; suggested objective functions; strategies for optimal system operation; and results of some optimal operation strategies for the hydrological year 1985/86. These results are monthly values of surface reservoir releases, pumping/recharge rates and locations, hydraulic heads in aquifer, and generated/consumed energy. In all cases, the comparison between these results and the actual policy for the conjunctive operation in the project area shows that the proposed optimal operation strategies represent a decisive improvement of the system operation.

12. Cosgrove, Donna M. and Gary S. Johnson, 2004. Transient response functions for conjunctive water management in the Snake River Plain, Idaho. Journal of the American Water Resources Association. P. 1469 - 1482.

    Abstract: Increasing demands on western water are causing a mounting need for the conjunctive management of surface water and ground water resources. Under western water law, the senior water rights holder has priority over the junior water rights holder in times of water shortage. Water managers have been reluctant to conjunctively manage surface water and ground water resources because of the difficulty of quantification of the impacts to surface water resources from ground water stresses. Impacts from ground water use can take years to propagate through an aquifer system. Prediction of the degree of impacts to surface water resources over time and the spatial distribution of impacts is very difficult. Response functions mathematically describe the relationship between a unit ground water stress applied at a specific location and stream depletion or aquifer water level change elsewhere in the system. Response functions can be used to help quantify the spatial and temporal impacts to surface water resources caused by ground water pumping. This paper describes the theory of response functions and presents an application of transient response functions in the Snake River Plain, Idaho. Transient response functions can be used to facilitate the conjunctive management of surface and ground water not only in the eastern Snake River Plain basin, but also in similar basins throughout the western United States.

13. Dappen, Patti and Free Colby, 2002. Land cover mapping for the Nebraska cooperative hydrology study in the Central Platte River Basin (COHYST). The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Colorado Convention Center, A/102/104/106, Denver Annual Meeting (Oct. 27-20, 2002), Session No. 102. T61. Geological Society of America.

    Abstract: Agriculture dominates the landscape of the Central Platte River Basin. Habitat loss has caused concern for the welfare of the millions of migratory birds that stop along the Platte on their way to northern breeding grounds. In response to the Platte River Cooperative Agreement between Nebraska, Colorado, and Wyoming, the Cooperative Hydrology Study in the Central Platte River Basin (COHYST) was established to develop hydrologic modeling and detailed studies in the Platte River Basin upstream of Columbus, NE. As part of the COHYST project, remote sensing, spatial, and field data have been incorporated to produce an accurate map of agricultural crops and other land cover in the Central Platte River Basin in 1997. Multi-date Landsat Thematic Mapper imagery was used to capitalize on the seasonal dynamics of the agricultural crops and native plant communities. Extensive crop and field data were used in collecting training sites used in the

supervised classification. Distinctions were made between irrigated and non-irrigated crops using field and ancillary data.

Comprehensive and current information on land cover and land use (especially irrigation and crop patterns) are critical to COHYST, since hydrologic conditions change in relation to crop dynamics. Future COHYST modeling efforts will require examination of historical and current agricultural land cover patterns. Current mapping efforts using 1982 and 2001 satellite imagery will also be discussed. More information about the project can be found at http://www.calmit.unl.edu/cohyst/.

14. Dvorak, Allison, 2000. Central Valley groundwater bank operations: hydrology, groundwater operating rule, and system operating rule effects on yield. Masters Thesis, University of California, Davis.

    Abstract: How would more aggressive operations of groundwater banks affect California's SWP (State Water Project) and CVP (Central Valley Project) water supply deliveries? Modeling experiments using the California water system simulation model, DWRSIM, show that aggressive re-operation of groundwater storage, both north and south of the Delta, can increase long-term average project deliveries by as much as 114 TAF (thousand acre feet). However, to obtain these benefits, the entire system must be re-operated to take advantage of increased groundwater storage flexibility. To make the experimental studies comparable with the base studies, all studies were operated with the same acceptable amount of project delivery shortages and the same level of acceptable Shasta Reservoir storages. Re-operation was shown to always result in long-term annual average benefits and often result in both long-term and critical period annual average benefits to project deliveries.

15. Fredericks, J. W., J. W. Labadie, and J. M. Altenhofen, 1998. Decision support system for conjunctive stream-aquifer management. Journal of Water Resources Planning and Management. Vol. 124, No. 2, p. 69-78, 42 refs.

    Abstract: A decision support system (DSS) was presented for conjunctive management of surface water and groundwater under prior appropriation. The DSS was constructed around the generalized river basin network flow model MODSIM which allowed access to input and output databases and modification and verification at all levels of the modeling process. The graphical user interface for the MODSIM DSS provided spatially referenced database capabilities so the user could create and link river-basin network objects on the display and populate and import data for that object interactively. Geographical information system tools were used to prepare grid-based spatial data for input into MODRSP, a modified version of the U.S. Geological Survey (USGS) three-dimensional finite-difference groundwater model MODFLOW. Response functions generated by MODRSP were provided to MODSIM for simulating spatially varied and time-lagged return/depletion flows from stream-aquifer interactions. Capabilities of the MODSIM DSS were demonstrated for a portion of the Lower South Platte River Basin, Colorado, USA. Results indicated significant differences between using groundwater response coefficients developed from preassigned stream depletion factor (SDF) values, as currently used in the basin, and those generated using a finite-difference groundwater model.

16. Hanson, Randall and Faunt Claudia, 2005. An Updated Hydrologic Model of California's Central Valley Using MODFLOW-2000 with the Farm Package. California Water and Environmental Modeling Forum, "Water and Environmental Modeling to Support Decision Making." Annual Meeting Abstracts, Asilomar Conference Grounds, 800 Asilomar Blvd, Pacific Grove, CA.

    Abstract: The USGS is revising and updating the CV-RASA model into a model that is capable of being more accurate and can be used to quantitatively address groundwater issues in the Central Valley. The ongoing USGS study has three tasks. The first task, "texture modeling," will address the objective of developing a better understanding of the internal architecture of the freshwater bearing deposits in the Central Valley. The second task, the "Farm Package", will address the objective of developing a systematic approach for estimating water budget components, which in

this study will be based upon the consumptive use of water by plants and available surface water deliveries and supplementary ground-water pumpage. The third task, "Ground-water Modeling," will address the objective of developing a model capable of being accurate at a scale relevant to management decisions, including water availability issues.

17. Hathaway, Deborah L. and Tom Ma, 2003. Modeling the sensitivity of shallow groundwater elevations in a riparian area to river flow and regional groundwater conditions. New Mexico Symposium on Hydrologic Modeling, August 12, 2003, Socorro, NM.

    Abstract: A groundwater flow model was developed to simulate the impacts of changes in river operations and regional groundwater conditions on the shallow groundwater environment in riparian areas. This modeling study was conducted along the San Joaquin River in California. Because the San Joaquin River setting is hydrologically similar to the Rio Grande in New Mexico, concepts derived from these sensitivity analyses can be related to our understanding of riparian groundwater conditions and seepage losses on the Rio Grande.

    The MODFLOW code was applied to the near-river area (riparian zone) along the San Joaquin River for a distance of approximately 150 miles. In this application, alternate river conditions area based on HEC-2 model-generated water surface profiles. Alternate regional water use conditions are represented by regional groundwater elevations at the boundary of the riparian zone groundwater model. Representative low, average and high regional groundwater conditions are derived from the historic record. The model is used to illustrate the sensitivity of river seepage and groundwater elevations to present and antecedent river discharge profiles and to regional groundwater conditions. The model results illustrate the dynamic and transient nature of surface water/groundwater interactions. Further, examination of the sensitivity of shallow groundwater conditions and surface water exchanges to river flow and regional groundwater conditions illustrates the need to develop process-based methods for quantifying surface water/groundwater exchanges, rather than adopting empirical functions that may not be applicable under conditions of interest.

18. Henszey, Robert J., Kent Pfeiffer, and Janet R. Keough, 2002. Linking surface and groundwater levels to riparian grassland species along the Platte River in Central Nebraska. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Colorado Convention Center, A102/104/106, Denver Annual Meeting (Oct. 27-20, 2002), Session No. 102. T61. Geological Society of America.

    Abstract: Although the values of riparian grasslands are well established, few quantitative data are available linking the underlying hydrology to the riparian plant species that support these important communities. This lack of information is especially critical along the Platte River in central Nebraska where riparian grasslands support a multitude of migratory birds, and where flow re-regulation to enhance habitat for endangered species is being considered. Ecologists use a host of techniques to quantify how environmental gradients, like surface and ground water levels, are linked to plant species. Nearly all these techniques, however, produce results that represent gradients in general terms such as low to high elevation, xeric to mesic, and low to high concentration. While ecologists understand the implications of these imprecise scales, managers responsible for making decisions affecting one or more of these gradients need information that is more precise. For our study, we preserved the scale and units of a water-level gradient ranging from below the surface to above the surface by using non-linear equations to fit plant species response curves to this dominant gradient. Non-linear equations are more useful than linear equations, like polynomials, because their coefficients can be interpreted with a biological meaning such as population peak, optimum gradient position, and ecological amplitude. Plant response to this water-level gradient was fit to 65 species. From among eight water-level statistics evaluated, the peak 10-day running-mean water level for the growing season produced the best plant-response fit, suggesting that several consecutive days of high water levels are more influential than low water levels or the frequency of high water levels. Land management practices affected 21 species by changing their frequency of occurrence and/or their position along the water-level gradient. Most species have an ecological amplitude from 35-80

cm along the water-level gradient, but a few have amplitudes as narrow as 20 cm. For these species with narrow amplitudes, a small permanent change in the 10-day high water level might completely displace their topographic location, possibly causing their aerial extent to expand or contract depending upon the available topography.

19. Jenkins, C. T., 1968. Computation of rate and volume of stream depletion by wells. Techniques of Water Resources Investigation. Chapter D1, Book 4, 17 pp. U.S. Geological Survey.

Abstract: When field conditions approach certain assumed conditions, the depletion in flow of a nearby stream caused by pumping a well can be calculated readily by using dimensionless curves and tables. Computations can be made of (1) the rate of stream depletion at any time during the pumping period or the following nonpumping period, (2) the volume of water induced from the stream during any period, pumping or nonpumping, and (3) the effects, both in rate and volume of stream depletion, of any selected pattern of intermittent pumping. Sample computations illustrate the use of the curve and tables. An example shows that intermittent pumping may have a pattern of stream depletion not greatly different from a pattern for steady pumping of an equal volume.

The residual effects of pumping, that is, effects after pumping stops, on stream flow may often be greater than the effects during the pumping period. Adequate advance planning that includes consideration of residual effects thus is essential to effective management of a stream-aquifer system.

20. Jenkins, M. W. and others, 2004. Optimization of California's water supply system: results and insights. Journal of Water Resources Planning and Management. Vol. 130, No. 4, p. 271-280, 10 refs.

Abstract: This paper presents results of a large-scale economic-engineering optimization model of California's water supply system. The results of this 4-year effort illustrate the value of optimization modeling for providing integrated information needed to manage a complex multipurpose water system. This information includes economic benefits of flexible operations, economic valuation of capacity expansion opportunities, estimating user willingness to pay for additional water, economic opportunity costs of environmental flows, and identification of promising conjunctive use and water transfer opportunities. The limitations of such modeling also are discussed. Overall, the results suggest improvements to system operation and water allocations with a statewide expected value potentially as high as $1.3 billion/year. Significant improvements in performance appear possible through water transfers and exchanges, conjunctive use, and various operational changes to increase flexibility. These changes also greatly reduce costs to agricultural and urban users of accommodating environmental requirements. Model results also suggest benefits for expanding selected conveyance and storage facilities.

21. Knapp, K. C. and L. J. Olson, 1995. The economics of conjunctive groundwater management with stochastic surface supplies. Journal of Environmental Economics and Management. Vol. 28, No. 3, p. 340-365, 23 refs.

Abstract: A model is considered for groundwater management with stochastic surface flows and artificial recharge. Theoretical analysis characterizes the decision rules and establishes conditions for convergence of socially optimal and common property withdrawals and pumping lifts to limiting probability distributions. An empirical application to Kern County, California, USA, found that optimal withdrawals were generally increasing in hydraulic head and decreasing in surface flows with some exceptions. Artificial recharge was not observed due to a combination of factors: recharge values to the aquifer were already large; and energy costs of pumping plus significant depth to groundwater reduce the demand for recharge. Optimal management implies relatively small gains over unregulated groundwater use when preferences are risk neutral.

22. Krapu, Gary L., 2002. Sandhill Cranes and the Platte River - A Closer Look. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Colorado Convention Center,

A102/104/106, Denver Annual Meeting (Oct. 27-20, 2002), Session No. 102. T61.Geological Society of America.

Abstract: A half million sandhill cranes stop for several weeks in spring in the Central Platte River Valley (CPRV) of Nebraska to obtain key nutrient needs before continuing their spring migration. Using satellite telemetry and other techniques, we and other USGS scientists currently are seeking a detailed understanding of the various facets of the relationship between the midcontinent sandhill crane population and the Platte River. We describe length of time individual radio-marked sandhill cranes spend at the Platte each spring and the role of the Central Platte River Valley in preparing the birds physiologically for migration and reproduction. When the cranes leave the Platte, we monitor their movements throughout the year with the aid of 30 g Platform-Transmitting Terminals attached to plastic leg bands. As a result, we have been able to examine the role of the Platte in meeting the needs of various subpopulations that breed from northern Siberia to eastern Ontario. Also, with radio-telemetry we are assessing the extent that individuals return to the same roost site at the Platte from one year to the next, and factors associated with roost-site selection.

23. Kress, Wade H., Benjamin J. Dietsch, and James C. Cannia, 2002. Use of continuous seismic profiling to differentiate geologic deposits underlying major canals in Western and Central Nebraska. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Colorado Convention Center, A102/104/106, Denver Annual Meeting (Oct. 27-20, 2002), Session No. 102. T61. Geological Society of America.

Abstract: Continuous seismic-reflection profiling (CSP) produces digital data capable of classifying subsurface lithology in a variety of marine, estuarine, riverine, and lacustrine settings. In August 2001, the U. S. Geological Survey, in cooperation with the Platte River Cooperative Hydrologic Study group, conducted a CSP survey in western and central Nebraska. CSP is useful in assessing the depth and profile of the bedrock surface underlying unconsolidated deposits and to determine the thickness of overlying unconsolidated deposits.

Typically test holes and surficial geologic mapping determine the depth and shape of the bedrock surface underlying unconsolidated deposits. However, this information is often either not in the area that needs to be defined or data locations are spaced too far apart to define adequately the bedrock surface. These problems lead to estimates of both the depth of the bedrock and the bedrock profile; however, these estimates can lead to incorrect assessments of the thickness of saturated zones used in numerical ground-water-flow models, which can accentuate inherent errors to a ground-water-flow model.

Preliminary interpretation of data collected for approximately 26 of the 90 miles surveyed using CSP has been completed, and showed that about 70 percent of the data examined so far exhibited reflectors corresponding to general unconsolidated depositional features. Alternatively, 23 percent of the data examined showed continuous definable reflectors that likely could be classified as bedrock and could be correlated with borehole drillers-log and geophysical log data.

The preliminary results indicate that the presence of gravel and boulders in unconsolidated materials beneath the canal probably absorbed and reflected most of the available acoustic energy, thereby weakening penetration of seismic signals in some areas. Most of the signals generated during data collection in seasonal canals (predominant in western Nebraska) did not penetrate the sediments adequately to identify specific geologic features, but were absorbed in the hard bed of the seasonal canals. In central Nebraska, data collected in perennial canals locally indicated reflectors corresponding to bedrock and produced the best results in the study.

24. Landon, Mathew K. and others, 2002. Estimation of riparian woodland evapotranspiration along the Platte River, Nebraska. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Colorado Convention Center, A102/104/106, Denver Annual Meeting (Oct. 27-20, 2002),

Session No. 102. T61. Geological Society of America.

Abstract: The U.S. Geological Survey and Nebraska Platte River Cooperative Hydrology Study Group are conducting a study to: (1) measure total evapotranspiration (ET) and estimate rates of ground-water use to satisfy ET consumptive demands (GWET) by riparian woodlands at two representative sites, and (2) calibrate models using the research data to estimate riparian GWET at other locations in the Platte River Basin in Nebraska. The study, based upon data collected from March 2002 to April 2004, will provide better-constrained estimates of GWET in the study area than presently exist and will improve understanding of the impacts of riparian vegetation on water availability.

Study sites were selected based upon analysis of land cover data, woodland surveys, and source-area extent calculations. The investigations at each site will include: (1) determining total ET using eddy-covariance and energy-balance sensors mounted on and around 90-foot tall towers extending 30 feet above the woodland canopy, (2) comparing estimates of GWET determined from ground-water hydrographs with those determined from soil-water and micrometeorological data, and (3) measuring precipitation throughfall to estimate evaporation of intercepted precipitation.

25. Lewis, Gary L. and Duane Woodward, 2002. COHYST - Nebraska's decision support system for meeting the obligations of the Platte River cooperative agreement. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Colorado Convention Center, A102/104/106, Denver Annual Meeting (Oct. 27-20, 2002), Session No. 102. T61. Geological Society of America.

Abstract: Eleven state and local agencies and eight partner organizations created the Cooperative Hydrology Study (COHYST) to develop detailed databases and regional groundwater models that would provide a scientifically defensible decision support system (DSS) to assist Nebraska in water management planning and in meeting its obligations under a 1997 Cooperative Agreement (CA) with Wyoming, Colorado and the U.S. Department of Interior. The CA calls for each state to implement a plan that would mitigate new depletions to the U.S. Fish and Wildlife Service (USFWS) target flows for critical habitat in the Platte River from Lexington to Chapman, NE. The COHYST model area covers 29,300 square miles of aquifers in the Platte River Basin from Columbus to 6 mi inside Wyoming and Colorado. The main product of COHYST is a set of three overlapping regional groundwater-flow models with sufficient detail to analyze the stream depletion effects of surface and groundwater management options. This paper describes the models and the detailed data sets developed or being developed for the modeling, including crop and land-use maps for1982, 1997, and 2001; changes in land use over time; crop water demand, net recharge, and runoff using a complex soil-water balance model; mapping of ten hydrostratigraphic layers from 1,700 existing and 300 new test holes; virtual measurements of riparian woodland evapotranspiration by eddy covariance methods, measurements of streambed hydraulic conductivity, temperature tracing of discharge to ground water, direct measurements of canal seepage, geophysical techniques to obtain lithology beneath canals, and measuring pumpage to confirm model parameters. Calibrated models exist with 160-ac cells but eventually could be refined to sub-regional models with 10-ac cells. Calibration of the models is described, as well as how the models are being used to delineate zones of hydrologically connected groundwater, to analyze mitigation plans, and to support local agencies in developing water management plans.

26. Luckey, Richard R. and others, 2002. Estimating ground-water discharge to streams for use in the Nebraska cooperative hydrology study (COHYST) model calibration. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Colorado Convention Center, A102/104/106, Denver Annual Meeting (Oct. 27-20, 2002), Session No. 102. T61. Geological Society of America.

Abstract: COHYST is producing ground-water flow models to analyze the effects of water-management activities proposed under the Three-State (CO, NE, WY) Cooperative Agreement. Ground-water discharge to streams is an important calibration data set for these models. This

discharge was estimated for 16 tributaries to and 7 reaches of the N. Platte River, 1 tributary to and 2 reaches of the S. Platte River, 3 tributaries to and 5 reaches of the Platte River, 12 tributaries to and 5 reaches of Frenchman Creek/Republican River, 3 reaches of the Loup River, and 3 tributaries to the Big Blue River. Ground-water discharge to streams was estimated using period-of-record fall (October-November) daily flows from stream flow gaging stations operated by the U.S. Geological Survey and Nebraska Department of Natural Resources. Spring and summer flows were not used because of diversions, returns of diversions, runoff from irrigation and precipitation, and evapotranspiration along the streams. Winter flows were not used because ice conditions can affect the accuracy of stream flow data. The lowest fall stream flows represent ground-water discharge to streams. For tributaries, the fall 7-day low flow with a recurrence interval of 5 years was used as the minimum estimate of ground-water discharge at the station and the 14-day, 2-year low flow was used as the maximum. For main-stem reaches, total fall downstream outflow minus total fall upstream inflow was computed for each year of record. The minimum estimate of ground-water gain or loss to the reach was the fall gain or loss with a recurrence interval of 5 years; the maximum estimate was the gain or loss with a 2-year recurrence interval. Long-term ground-water discharge to tributaries of the N. Platte, S. Platte, and Platte Rivers upstream of the Loup River ranged from zero for Wood River to 146 cubic feet per second (cfs) for Birdwood Creek. Ground-water discharge to tributaries of the Frenchman Creek/Republican River ranged from zero for several tributaries to 33 cfs for Medicine Creek (pre-dam). Ground-water discharge to main-stem reaches ranged from a gain of 150 cfs on the N. Platte River from Mitchell to Minatare (18 mi) to a loss of 150 cfs on the Platte River from Odessa to Grand Island (56 mi).

27. Marino, M. A., 2001. Conjunctive management of surface water and groundwater. P. 165-173, 30 refs., Price: pounds-sterling 47.75. Wallingford, UK: IAHS Press.

Abstract: Because of the intensifying competition by urban, agricultural, and environmental concerns for available water and the increased difficulty in constructing large-scale projects, it is of paramount importance that basinwide management strategies be considered that include conjunctive use of surface water and groundwater. This paper discusses simulation and optimization models and decision-support tools that have proven to be valuable in the planning and management of regional water supplies. Also discussed are conjunctive water management issues in California, USA, as well as water management approaches for effectively dealing with climate change.

28. Matsukawa, J., B. A. Finney, and R. Willis, 1992. Conjunctive-Use Planning in Mad River Basin, California. Journal of Water Resources Planning and Management [ASCE] JWRMD5. Vol. 118, No. 1/2, p 115-132, 8 fig, 3 tab, 24 refs. University of California Water Resources Center Grant W-694.

Abstract: A conjunctive use management model was developed that can be used to develop planning and operational strategies for a river basin. In contrast to previous investigations, the conjunctive use model explicitly incorporates (1) the hydraulics of the surface and groundwater systems, and (2) water supply, hydropower, and groundwater cost and benefit objectives. Operational constraints include hydropower production limits, water quality constraints on the blended surface water and groundwater used to meet the municipal demand, and minimum instream flow needs downstream of the water supply abstraction point. The model was applied to the Mad River basin in Northern California. Optimal planning policies were developed for the water resource system. The optimization model was solved using MINOS, a large-scale, nonlinear programming algorithm. The results for the one-year planning horizon showed that it may be advantageous for the reservoir to store water so that a maximum hydraulic head will be obtained for maximizing hydropower production revenue through releases. Municipal irrigation requirements in the summer months resulted in a higher willingness to pay in the water supply benefit function. Annual groundwater pumping costs can be decreased by 3% if wells are developed in areas more suitable for groundwater extraction. It is concluded that conjunctive use management is a useful tool for multiobjective water resources planning problems.

29. McHugh, Kathleen M., 2003. Western water law and the stream-aquifer system and how models are used to determine permitting and compliance of rules governing ground and surface water. University of

Arizona Master's Thesis.

Abstract: Scientific reality shows that the stream-aquifer system is not two separate entities, but is one. This thesis' purpose is threefold: (1) to provide and explain the basic hydrological principles that all decision makers should be aware of and understand; (2) to present a current summary of both surface water law and groundwater law in several western states, and specifically, the laws pertaining to groundwater/surface water interaction; and (3) to present a discussion of a few models being used in assessing how section 2's laws are affecting the system as a whole. Section Two presents the pertinent groundwater and surface water laws for Arizona, Colorado, Kansas, Nebraska, New Mexico, Oregon, Texas, and Washington. This area highlights the laws that pertain to the interaction between surface water and groundwater. In many of these states the evolution of these laws is also provided through legislative bills, acts, and court cases. Finally, Section Three discusses several models or techniques being used to assess the effects these laws have on the groundwater/surface water system.

30. McKinney, Daene C. and others, 1999. System-Wide Initiative on Water Management (SWIM), Modeling Water Resources Management at the Basin Level: Review and Future Directions. 60 p.

Abstract: This review paper addresses the most common river basin management tools, including water resources management modeling at the subsystem and river-basin levels. At the subsystem level, the tools of reservoir operation, groundwater management, conjunctive surface water and groundwater management as well as irrigation and drainage management are reviewed in the context of integrated water quantity and quality management.

The conjunctive management of surface water and groundwater can increase the efficiency, reliability, and cost-effectiveness of water use in a stream-aquifer system. Several simulation/optimization procedures have been developed to study conjunctive use problems. Longer-term problems often address water quality issues in conjunctive use management, especially (ground) water quality and salinity changes in irrigation systems.

Simulation is the preferred technique to assess water resources system responses to extreme, nonequilibrium conditions, like droughts, and thereby to identify the system components most prone to failure, or to evaluate system performance relative to a set of sustainability criteria over a long time period, like climate change, or to rapidly changing priority demands, like accelerated municipal growth. The range of river basin simulation models can be classified into flow simulation models, quality simulation models, water rights simulation models, and comprehensive simulation models.

Optimization models are based on an objective function and constraints and can include social value systems in the allocation of water resources. They can be hydrology-inferred or based on economic criteria of optimal water allocation. However, optimization models usually contain a simulation component to characterize the hydrologic regime, and are thus usually referred to as integrated simulation and optimization models. A wide range of models of this type has been developed, often including a basin or subbasin, but mostly focusing on one sectoral water user or a few of them.

It is at the basin level that hydrolic, agronomic, and economic relationships can be integrated into a comprehensive modeling framework and, as a result, policy instruments, which are designed to make more rational economic use of water resources, are likely to be applied at this level. Improved basin-scale modeling of water policy options will be an important direction for water management research in the immediate future. Efficient and comprehensive analytical tools are needed to make the rational water allocation decisions necessary to achieve sustainable water use strategies for many river basins. The future direction for modeling will lie in GIS-based decision support systems that integrate economic, agronomic, institutional, and hydrologic components.

31. Menenti, M. and others, 1992. Appraisal and optimization of agricultural water use in large irrigation schemes: II. Applications. Water Resources Management. Vol. 6, No. 3, P. 201-221, 12 refs.

Abstract: In this paper, the theoretical approach presented in a companion paper is demonstrated by means of case studies on the irrigation schemes of Rio Mendoza and Rio Tunuyan in the Province of Mendoza, Argentina. The object of the case studies was the determination of optimal allocation of surface water to reduce the use of groundwater. Current and optimal conjunctive allocation of ground and surface water is studied by means of the developed simulation and optimization models. The second case study was designed on the basis of the experience gathered during the first one. Each step of the case studies is compared. The comparison between the two case studies illustrates how the proposed approach should be applied when the amount and quality of available data are different. For the second more detailed study, the following physical characteristics of all terminal nodes were determined: on-farm rotational intervals, mean water application depth, actual soil water storage capacity, crop water requirements, depth of groundwater table, aquifer transmissivity, and efficiency of groundwater use. The simulation study showed that system performance is sensitive to changes in the water application depth. The optimization approach was used to demonstrate that a cost-saving reassignment of water by conjunctive use of ground- and surface water would enable the total water requirements of the scheme to be met over the year.

32. Miller, S. A. and others, 2003. Regional scale modeling of surface and ground water interaction in the Snake River Basin. American Water Resources Association. Vol. 39, No. 3, p. 517-528.

Abstract: Changes in irrigation and land use may impact discharge of the Snake River Plain aquifer, which is a major contributor to flow of the Snake River in southern Idaho. The Snake River Basin planning and management model (SRBM) has been expanded to include the spatial distribution and temporal attenuation that occurs as aquifer stresses propagate through the aquifer to the river. The SRBM is a network flow model in which aquifer characteristics have been introduced through a matrix of response functions. The response functions were determined by independently simulating the effect of a unit stress in each cell of a finite difference groundwater flow model on six reaches of the Snake River. Cells were aggregated into 20 aquifer zones and average response functions for each river reach were included in the SRBM. This approach links many of the capabilities of surface and ground water flow models. Evaluation of an artificial recharge scenario approximately reproduced estimates made by direct simulation in a ground water flow model. The example demonstrated that the method can produce reasonable results but interpretation of the results can be biased if the simulation period is not of adequate duration.

33. Morel-Seytoux, H. J., 2001. Value and modeling of conjunctive use of surface and groundwaters in basin management. p. 183-190, Price: pounds-sterling 65.00. Wallingford, UK: IAHS Press.

Abstract: In planning exercises, the interaction between stream and aquifer must be properly described and incorporated in the day-to-day management of the resource within a complex system of economic interests, laws and administrative rules. The manner in which the modeling system Stream-Aquifer Model for Management by Simulation and Optimization was used to evaluate the worth of an augmentation plan in Colorado, USA, is reviewed. The adequacy and benefits of the plan are presented. They demonstrate clearly the value of having modeled the system with a tool capable of representing it at a sufficient level of physical detail. Four original mathematical and computational features are discussed: (a) the use of a "scanning subgrid"; (b) "sequential re-initialization" through the concept of (c) the "Artificial Steady-State pumping pattern"; and (d) reach transmissivity.

34. Onta, P. R., A. Das Gupta, and R. Harboe, 1991. Multistep Planning Model for Conjunctive Use of Surface-Water and Ground-Water Resources. Journal of Water Resources Planning and Management [ASCE] JWRMD5. Vol. 117, No. 6, p. 662-678, 3 fig, 6 tab, 20 refs, 2 append.

Abstract: A three-step modeling approach has been developed for comprehensive analysis of the planning problem involving integrated use of surface and groundwater in irrigation. In the first stage, a stochastic dynamic programming (SDP) model, which considers most of the interacting processes of the conjunctive use system, is used to determine long-term operation policy guidelines for each alternative considered. Then a lumped simulation model is used to evaluate the alternative plans and

policies, considering a number of mutually related synthetic sequences of stream flow and rainfall. Various economic (cost and benefit) as well as risk-related (reliability, vulnerability, and resiliency) performance measures and their tradeoffs are evaluated. Finally, a multiple-criteria decision-making method (compromise programming) is used to select the most satisfactory alternative plan for indicating the system design (pumping and diversion canal) capacities and water allocation policies. Important policy and management implications are drawn from sensitivity analyses with respect to unit pumpage cost, irrigation system efficiency, and recharge coefficient.

35. Peralta, A. W. and R. C. Peralta, 1986. Sustained Groundwater Yield and Consumptive Use via Target Levels in a Reasonable Use State. Water Resources Law. Pp. 235-243, 1 fig, 1 tab, 15 ref. Proceedings of the National Symposium on Water Resources Law, Chicago, Illinois.

Abstract: Groundwater and surface water regional models can be created to develop water use strategies that maximize achievement of predetermined regional objectives. In addition, the water use strategies developed by such planning models can: assure the sustained availability of groundwater; make best use of surface water resources while they are available for recharge to an aquifer or for diversion to riparian or nonriparian lands; and successfully coordinate the use of groundwater and surface water resources that hydrologically interact with each other. Implementing a sustained yield groundwater management strategy that can sustain approximately the same amount of pumping year after year at each pumping location will ultimately result in the development of a 'steady-state' water table, piezometric or potentiometric surface. Let 'potentiometric surface' refer to the water table or piezometric surface. This steady-state potentiometric surface is a 'target' surface that, when properly designed, assures: adequate saturated thicknesses for existing or planned wells; adequate saturated thickness to permit additional groundwater pumping in time of drought; and movement of an 'appropriate' amount of water between the district's aquifer and connected aquifers or streams. In summary, water users adhering to such a groundwater management strategy should enjoy some degree of protection from successful litigation charging 'unreasonable use'. Furthermore, the use of diverted river water can be coordinated with the sustainable use of groundwater to maximize the total use of available water. There is not now any major legal impediment to conjunctive use of groundwater and surface water in Arkansas. It is hoped that future acts of the legislature, courts and administrative agencies will preserve presently existing options.

36. Peralta, R. C., R. R. A. Cantiller, and J. E. Terry, 1995. Optimal large-scale conjunctive water-use planning: case study. Journal of Water Resources Planning and Management. Vol. 121, No. 6, p. 471-478, 33 refs.

Abstract: Optimal sustained groundwater yield and conjunctive water-use strategies are presented for NE Arkansas, USA, based on water demands projected for the five decades of 1920-2039. Each strategy consists of spatially and temporally distributed values of groundwater and surface-water use. The 33 7000 km2 region has much irrigation and is very dependent upon groundwater. Groundwater flow simulation/optimization (S/O) models were used to accommodate increasing water needs for alternative future management scenarios. The S/O models employ a sequential steady-state embedding approach, and contain over 1600 embedded groundwater and river-volume balance constraints per decade (stage).

37. Peterson, Steven M. and others, 2002. Construction and calibration of the Nebraska cooperative hydrology study (COHYST) groundwater-flow models. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Colorado Convention Center, A102/104/106, Denver Annual Meeting (Oct. 27-20, 2002), Session No. 102. T61.Geological Society of America.

Abstract: The primary products of COHYST are groundwater-flow models that can be used to analyze the effects of water-management activities proposed under the Three-State Cooperative Agreement between Nebraska, Wyoming and Colorado. A fundamental step in this process is the calibration of groundwater-flow models of the area.
The 29,300 square-mile study area in central and western Nebraska was divided into three model

units, which overlap adjoining units by at least 12 linear miles along the river (COHYST Flow Modeling Strategy, at http://cohyst.nrc.state.ne.us/cohyst_data.html). Ideally, initial models should simulate conditions prior to any surface-water or groundwater development, when the flow system was in dynamic equilibrium (steady state). However, surface water irrigation occurred in the study area as early as the 1890s. The lack of data makes formal calibration for that time period impractical. The flow system is assumed to have been in equilibrium with the effects of early canal operations by the time major groundwater development for irrigation began in the 1950s. Therefore, the pre-groundwater development period was defined as prior to 1946. Sufficient calibration data exist for 1946 and later over much of the area. Pre-groundwater development models were calibrated against observed water levels and estimated groundwater discharge to streams.
Initially, single-layer groundwater-flow models were constructed with 4 square- mile cells. The final goal is to construct and calibrate transient groundwater-flow models for the period 1949-1997, with Ľ square-mile cells and multiple hydrostratigraphic layers. Several intermediate models were constructed to incorporate increasing complexity as refined geologic or net recharge data became available. All models were calibrated against observed water levels and groundwater discharge to streams, and transient models also were calibrated against water-level change maps.

38. Philbrick, C. R. and P. K. Kitanidis, 1998. Optimal conjunctive-use operations and plans. Water Resources Research Vol. 34, No. 5, p. 1307-1316 (10 p.), 50 refs.

Abstract: Heuristic or intuitive rules based on experience may not be efficient when applied to the management of water supply systems that contain both surface and subsurface storage. In particular, rules that assign subsurface storage the role of a backup to surface storage do not recognize the different capabilities of surface and subsurface storage. We demonstrate how to incorporate the different capabilities of surface and subsurface storage in appropriately cautious long-term control of conjunctive-use systems. We also demonstrate how these results may be used to evaluate the benefit of adding groundwater supplies to an existing surface water supply system.

39. Pulido-Velazquez, M., M. W. Jenkins, and J. R. Lund, 2004. Economic values for conjunctive use and water banking in southern California. Water Resources Research. Vol. 40, No. 3, 22 refs., W03401.

Abstract: The potential and limitations of conjunctive use of surface and groundwater are explored for southern California's water supply system. An economic-engineering network flow optimization model, CALVIN, is used to analyze the economic and reliability benefits from different conjunctive use alternatives. Flexible management of additional conjunctive use facilities and groundwater storage capacity under flexible water allocation can generate substantial economic benefits to the region. Conjunctive use adds operational flexibility to take better advantage of water market transfers, and transfers provide the allocation flexibility to take better advantage of conjunctive use. The value of conjunctive use programs along the Colorado River Aqueduct, in Coachella Valley, and north of the Tehachapi Mountains under economically optimized operation of the system is examined. Results reveal reductions of economic demand for increased imports into southern California, suggest changes in the system operations, and indicate significant economic benefits from expanding some conveyance and storage facilities.

40. Ratkovich, D. Ya., 1998. Feasibility of conjunctive use of surface water and groundwater in a water resources system. Water Resources. Vol. 25, No. 1, p. 85-98.

Abstract: The regularities of water deficiency formation during the operation of water resources systems involving surface water and groundwater are considered. Such issues in the water budget deficiency as the frequency of water-deficient years, their grouping, and the extent of water deficiency are discussed.

41. Restrepo, J. I. and H. J. Morel-Seytoux, 1989. Calibration study with SAMSON: a model for conjunctive operation of surface and groundwaters. No. 180, p. 241-249, 5 refs. IAHS Publication.

Abstract: The SAMSON model was used to reproduce historical records of flows at several gauges

on the South Plate River between Denver, Colorado and the Nebraska state line, USA. In this stream-aquifer system the water is directed and reused 3 times on average primarily for agricultural purposes in a semi-arid environment. SAMSON was used to predict the flows during wet and dry periods when river regimes differ widely. The model demonstrated its ability to adapt to these conditions and gave consistently reasonable results. The simulation version was applied to the South Platte River basin, Colorado, with encouraging results. The wide flexibility in SAMSON for describing river basin behavior allowed a realistic reproduction of operations and reactions of a stream-aquifer system subject to multiple uses.

42. Rus, David L. and others, 2002. Streambed hydraulic conductivity in Central and Western Nebraska. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist (*GSA Hydrogeology Division*), Colorado Convention Center, A102/104/106, Denver Annual Meeting (Oct. 27-20, 2002), Session No. 102. T61. Geological Society of America.

Abstract: Streambed hydraulic conductivity (K_s) is a fundamental parameter controlling the exchange of water across the stream-aquifer interface. However, in central and western Nebraska, few data on this parameter are available. The U.S. Geological Survey, in cooperation with the Nebraska Platte River Cooperative Hydrology Study (COHYST) and the University of Nebraska-Lincoln, performed successive studies to better define K_s in streams of central and western Nebraska. The results of a pilot study to determine the most appropriate instream technique for measuring K_s were that in the sandy streambeds of seven sites falling-head permeameter tests analyzed using the Hvorslev solution were the most suitable for characterizing the K_s of the top foot of the sediments. However, in cases where ground-water/surface-water interactions were restricted by relatively fine-textured sediments present below the top foot, alternative methods were utilized to determine K_s. Following the pilot study, streambed samples were collected at 58 sites to determine sediment texture to a depth of 4 feet. At 15 sites where sediments with the finest texture were deeper than 1 foot, vertical profiles of K_s were determined using slug-tests. At 22 sites without a low-permeability layer deeper than 1 foot, falling-head permeameter tests were performed. Results from these studies indicate that in central and western Nebraska K_s is generally higher in the sandy streambeds of main-stem rivers, whereas tributary streams located outside the floodplains of those main-stem rivers are characterized by lower K_s values.

43. Schmidt. W., R.T. Hanson, and T. Maddock, 2004. Simulation of Conjunctive Agricultural Water Use with the new FARM package for MODFLOW-2000. 2004 AGU Fall Meeting.

Abstract: A new Farm Package (FMP) was developed for the U.S. Geological Survey's groundwater modeling program, MODFLOW-2000 (MF2K), to estimate irrigation water allocations from conjunctively used surface and ground water. The FMP package dynamically integrates irrigation water demand, surface and ground-water supply, and return flow from excess irrigation. Routed surface-water delivery is optional, but can be simulated by coupling the FMP package with the Stream flow Routing Package (SFR1). Applying MF2K with the FMP and SFR1 packages facilitates estimating the allocation of surface and ground-water to farms for simulations of historical calibration or future projections directly within MF2K. These simulations also can be useful for assessing water rights issues and operational decisions as well as for non-drought versus drought supply and demand strategies. Estimates of historic pumpage may be particularly useful where well pumpage has not been recorded, such as agriculture in the southwestern United States. Estimates of future pumpage may be facilitated through the use of climate-model predictions to generate forecasts of potential water supply and demand for irrigation. Legal questions such as adjudications and appropriative water rights also could be assessed with simulations that use the FMP package in areas where there is a history of land use but no direct or complete record of water use. Operational decision in irrigation management depends on the ability to estimate conjunctively used surface-water and groundwater allocations just prior to or during the growing season. Conjunctive management of surface and ground-water is especially needed for periods when the proposed water supply is thought to be insufficient to meet the water demand. Simulations with the FMP package offer several choices of drought policy scenarios, such as acreage optimization that facilitates

assessing an economically optimal conjunctive management. The FMP package maintains a dual mass balance of a farm budget and a groundwater budget. Flows between these two budgets are accommodated by head-dependent inflows and outflows, such as the actual evapotranspiration or transpiration from groundwater. All flows of interest, such as irrigation demand, surface-water and groundwater supply, and excess irrigation return flow may depend on these head-dependent inflows and outflows. Consumption of water by individual crops from each farm is simulated with steady-state transpiration, varying with changing water level that is approximated in FMP by an analytical solution. These solutions were validated by soil column simulations with the variably saturated flow model HYDRUS2D. When irrigation demand in the farm budget cannot be sufficiently supplied by surface or ground water, a distortion of mass balance occurs. The FMP package provides the user with several drought policy response options including deficit irrigation, water stacking, and acreage optimization. A hypothetical example with 55 scenarios that represent 5 drought policy scenarios each with 11 parameter-group scenarios demonstrates the consistency and utility of the FMP package under different irrigation conditions. The first real-world application of `MF2K with FMP and SFR1 packages' was a model for the southern Rincon Valley, along the Lower Rio Grande of New Mexico, within the Elephant Butte Irrigation District. Another larger scale application of MF2K with FMP is being implemented by updating the USGS model of the Central-Valley Regional Aquifer System Analysis in California.

Additional notes from
http://www.sahra.arizona.edu/research/IM/display.html?mode=displayProj&proj_id=M08

1. Dissertation of Wolfgang Schmidt:
"A Farm Package for MODFLOW-2000: Simulation of Irrigation Demand and Conjunctively Managed Surface-Water and Ground-Water Supply, PhD Dissertation, University of Arizona at Tucson, 278 p."

2. Oral Presentation: "Schmidt, W., Hanson, R.T., and Maddock, T., 2004, A Farm Package for MODFLOW-2000: Simulation of Irrigation Demand and Conjunctively Managed Surface-Water and Ground-Water Supply, Oral and Poster Presentation, Annual Conf. of SAHRA. - October 13 - 16, 2004, Albuquerque, New Mexico."

3. Oral Presentation: "Schmidt, W. and Maddock III, T., 2004, Interstate and International Conjunctive Surface-Water/Ground-Water Management using the FARM Package for MODFLOW-2000, - Transboundary Waters Management Symposium, Proceedings Paper, Tucson, Arizona, November 16-19, 2004."

4. Poster Presentation AGU, San Francisco: "Schmidt, W., Hanson, R.T., and Maddock III, T., 2004, Simulation of Conjunctive Agricultural Water Use with the new FARM package for MODFLOW-2000, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract H33D-0494, Poster Presentation."

5. Code and documentation into review by end of 01/2005 and available by 08/2005 as USGS publication.

6. Expansion of the code to estimate groundwater and surface-water components under several choices of drought policy scenarios such as "optimization of acreage", "deficit irrigation", and "water-stacking for priority crops."

7. The Farm Package has been tested and applied to a pilot project area in the Southern Rincon Valley within the Elephant Butte Irrigation District, NM: Supervision: Dr. J.P. King, NMSU, Ph.D. Student: Suzanne Tillery, NMSU

44. Schmidt, Wolfgang and Thomas Maddock III, 2003. Capabilities of the New FARM Package for MODFLOW-2000. Poster Presentation; SAHRA 3rd Annual Meeting, Tucson Inn Suites Hotel.

Abstract: A new FARM package (FMP) was developed for MODFLOW-2000. The main objective

was to offer irrigators a tool for conjunctive management during drought situations. The program allows several choices of drought policy scenarios such as "optimization of acreage," "deficit irrigation," and "water-stacking for priority crops." Being linked to the Stream-Flow Routing Package of MODFLOW, the program is able to simulate surface-water supply and farm irrigation demand, as well as to estimate supplemental groundwater use required to sustain the crops growth for each of the drought scenarios. Water managers may manipulate the surface-water and groundwater supply in a model by limiting diversions from canals/laterals to certain allotments and by restricting well discharge rates to maximum capacities.

Irrigation demand and supply are in part subject to head-dependent sources and sinks such as evapotranspiration from groundwater and leakage between canals and aquifer. The program algorithms needed to account for those head-dependent boundary conditions (net-recharge from farms, demand-dependent farm well discharge, stream-aquifer leakage), for the inter-linkage between them, and to update source/sink term flow rates according to the application of a specific drought scenario.

45. Scott, M. J. and others, 2004. Water exchanges: tools to beat El Nino climate variability in irrigated agriculture. American Water Resources Association. Journal. Vol. 40, No. 1, p. 15-31, 40 refs.

Abstract: Using a case study of the Yakima River Valley in Washington State, this paper shows that relatively simple tools can be used to forecast the impact of the El Nino phenomenon on water supplies to irrigated agriculture, that this information could be used to estimate the significantly shifted probability distribution of water shortages in irrigated agriculture during El Nino episodes, and that these shifted probabilities can be used to estimate the value of exchanges of water between crops to relieve some of the adverse consequences of such shortages under western water law. Further, recently devised water-trading tools, while not completely free under western water law to respond to forecasted El Nino episodes (ocean circulation patterns), are currently being employed during declared drought to reduce the devastating effects of water shortages in junior water districts on high valued perennial crops. Additional institutional flexibility is needed to take full advantage of climate forecasting, but even current tools clearly could prove useful in controlling the effects of climate variability in irrigated agriculture. Analysis shows the significant benefit of temporarily transferring or renting water rights from low-value to high-value crops, based on El Nino forecasts.

46. Seymour, K. J. and others, 1998. The Fylde Aquifer - a case study in assessing the sustainable use of groundwater resources. P. 253-267, 8 refs. Chichester, UK: John Wiley & Sons Ltd.

Abstract: A study of the Fylde aquifer in northern England used an integrated, multi-functional approach to evaluate the mechanisms of groundwater recharge, groundwater flow and the interaction between groundwater and surface water. The work involved a review of a local conjunctive use scheme, the development of an integrated numerical model and the investigation of a series of abstraction/climatic scenarios.

47. Shannon, T. and others, 2000. Integration of GIS and River Basin Network Flow Modeling. 2000 ESRI User Conference Proceedings, San Diego, CA.ESRI.com Library.

Abstract: The U.S. Bureau of Reclamation has completed a major study that documents the economic, environmental and social impacts of annually delivering up to 1,427,000 acre-feet as flow augmentation for various fishery species that live and pass through the Lower Snake River, Idaho. The generalized river basin network flow model MODSIM was applied by Reclamation for this study due primarily to its unique capability of integrating the physical, hydrologic, and administrative aspects of evaluating the impacts of various flow augmentation scenarios. MODSIM includes the capability of incorporating spatially distributed stream-aquifer response coefficients generated from the USGS MODFLOW model. GIS plays a major role in synthesizing these spatially distributed response coefficients for inclusion into MODSIM. This paper presents prototype software which provides a metadata framework for linking GIS coverages with the procedural MODSIM river basin network flow model, with application to the Lower Snake River flow augmentation study.

48. Silka, L. R. and A. G. Kretschek, 1983. Incorporation of Predicted Future Climatic Effects into Simulations for Ground Water Resource Evaluations. P. 286-294, 7 fig, 1 tab, 24 refs. Proceedings of NWWA Western Regional Conference on Ground Water Management. San Diego, CA. National Water Well Association, Worthington, OH.

Abstract: Most predictions of groundwater resources are based upon the climatic patterns of the past century and the assumption that these patterns are static. If this important factor is neglected in planning, serious errors may be incorporated into the planning process. It is generally agreed that climate will undergo fluctuations in the near future, particularly a general warming trend; however, contention does exist concerning the magnitude and direction of these changes. For most hydrologic projects a 50 to 100-year climatic record is needed; for waste disposal, hundreds to thousands of years. For the Western U.S. hydrologic records go back only about 100 years; most continuous records for the same station are no longer than 40 years. Both proxy and historic records can be used to predict climatic events. For the predicted warming trend, the outlook for the status of water resources in the central and western states is not optimistic. A conservative scenario would demand that precipitation is diminished and recharge to groundwater drastically reduced. Conjunctive simulation of surface and groundwater becomes even more important. For example, the past simplifications in groundwater modeling of representing surface water bodies as constant head nodes should be changed to variable flux, head dependent boundaries.

49. Stansbury, J. and others, 1991. Decision Support System for Water Transfer Evaluation. Water Resources Research WRERAQ. Vol. 27, No. 4, p. 443-451, 6 fig, 3 tab, 21 refs.

Abstract: As the United States has changed from a young water economy to a mature one, there has been greater competition among water users (e.g., irrigators and municipalities) and more complex problems for water managers. A decision support system (DSS) was developed to help decision makers analyze the economic, social, and ecological ramifications of water transfers. Such a DSS is needed because the United States is evolving from a development-oriented water economy to a more complex one that emphasizes conservation and reallocation (i.e., transfers). The DSS consists of three main modules: (1) a conjunctive surface-ground water model, (2) an impact analysis segment, which uses a geographic information system (GIS) that integrates model output with information from the study area to estimated economic, social, and ecological impacts, and (3) a multicriteria decision making algorithm that ranks the transfer schemes based on trade-offs of indicators which are assembled into a hierarchical structure. Ten different water transfer alternatives were examined in a case study to demonstrate the application of the proposed DSS. The study area consisted of Gosper, Phelps, and Kearney Counties in south-central Nebraska. The area is an agricultural region having significant groundwater reserves in the Ogalalla and similar aquifers. The major stream in the study area is the Platte River. It was found that the DSS can be a valuable aid for water managers because it: forces consideration of a wide range of impacts; allows complex technical information to be incorporated into the decision making process; users readily available personal computers; employs GIS to facilitate analysis and interpretation of the results; uses accessible and easily understood weighting systems that establish confidence and facilitate sensitivity analysis; and, provides final trade-off analysis in graphical form.

50. Stillwater, Leslie, 2005. Water Rights and Flow Distribution Modeling Using ModSim. California Water and Environmental Modeling Forum "Water and Environmental Modeling to Support Decision Making."

Abstract: River system management models provide the cornerstone hydrologic analyses and investigations for water conservation, water management, flow augmentation, conjunctive use of surface water and groundwater, water availability, and many other planning and operations studies. The river systems management model, MODSIM, is unique in its ability to efficiently simulate the distribution of flows subject to Western Water Law (i.e., natural flow rights and Reclamation storage contracts), as well as other complex operating policies such as implicit and explicit exchanges of stored and natural flows, water transfers, rent pool agreements, and minimum stream flow requests. The network linear flows algorithm which drives the solution process in MODSIM streamlines the representation of water law and policy and allows the user to perform these tasks with considerably

less effort and coding than other modeling tools. The MODSIM model of the Boise River, a tributary to the Snake, demonstrates the combined simulation of complex operations policy, natural flow rights, and storage contracts.

51. Wagner, Brian J., 1995. Recent advances in simulation-optimization groundwater management modeling. Rev. Geophys. Vol. 33 Suppl., American Geophysical Union.

Abstract: The investigations described in this review demonstrate the accelerated pace of research into simulation-optimization groundwater management methods. Major strides have been made to allow the formulation and solution of complex groundwater management problems. The five key aspects of recent research include: (1) improved formulation and solution techniques for solving stochastic groundwater management problems, (2) methods that link groundwater management modeling with parameter estimation and sampling network design, (3) dynamic groundwater management methods that enable the design of efficient time-varying groundwater control strategies, (4) methods for solving combinatorial groundwater management problems, and (5) groundwater quality management models that account for nonequilibrium transport of multiple contaminants.

Most research reviewed in this paper focused on simulation and optimization methods for attacking the important problem of aquifer remediation design. Many types of problems related to aquifer remediation remain to be solved. These include optimal management of contaminant transport with non-linear multicomponent reactions; remediation design for multiphase flow and transport; and optimal design involving in situ chemical and biological remediation. Naturally, these problems will have to be formulated within a stochastic framework to account for model uncertainty, so continued advancement in the area of stochastic simulation-optimization methods is very important.

52. Watkins, D. W. Jr. and D. C. McKinney, 1999. Screening Water Supply Options for the Edwards Aquifer Region in Central Texas. Journal of Water Resources Planning and Management. Vol. 125, No. 1, p. 14-24.

Abstract: A screening model is developed to support the selection of alternatives for meeting future water demands and protecting sensitive ecosystems in the Edwards aquifer region of central Texas. Important attributes of the model are its basis on existing ground- and surface-water simulation models and its incorporation of uncertainty in future supplies and demands. The model is used to evaluate trade-offs involving environmental and economic risks and to identify water resources alternatives that promise to be robust (i.e., those that can be managed in a flexible manner to meet society's goals under a wide range of hydrologic scenarios). Use of the model to help determine conjunctive surface- and ground-water management policies is also demonstrated. Although limited benefits can be obtained through more coordinated operation policies, results indicate that either large investments in infrastructure or substantial reductions in projected water use will be required to meet environmental goals with a high degree of reliability.

53. Yan, Jiansheng and K. R. Smith, 1994. Simulation of integrated surface water and ground water systems - Model formulation. Water Resources Bulletin. Vol. 30, No. 5, p. 879-890.

Abstract: The unique characteristics of the hydrogeologic system of south Florida (flat topography, sandy soils, high water table, and highly developed canal system) cause significant interactions between ground water and surface water systems. Interaction processes involve infiltration, evapotranspiration (ET), runoff, and exchange of flow (seepage) between streams and aquifers. These interaction processes cannot be accurately simulated by either a surface water model or a ground water model alone because surface water models generally oversimplify ground water movement and ground water models generally oversimplify surface water movement. Estimates of the many components of flow between surface water and ground water (such as recharge and ET) made by the two types of models are often inconsistent. The inconsistencies are the result of differences in the calibration components and the model structures, and can affect the confidence level of the model application. In order to improve model results, a framework for developing a model which integrates a surface water model and a ground water model is presented. Dade County,

Florida, is used as an example in developing the concepts of the integrated model. The conceptual model is based on the need to evaluate water supply management options involving the conjunctive use of surface water and groundwater, as well as the evaluation of the impacts of proposed well fields. The mathematical structure of the integrated model is based on the South Florida Water Management Model (SFWMM) (MacVicar et al., 1984) and A Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW) (McDonald and Harbaugh, 1988).

54. Young, Robert A., 2005. Determining the Economic Value of Water, Concepts and Methods. 357 pp.

Abstract: Water provides benefits as a commodity for agriculture, industry, and households--and as a public good for scenic values, waste assimilation, wildlife habitats, and recreational use. However, even as the nature and needs of economies change, water continues to be allocated to other than high priority uses, water quality continues to decline, environmental uses get inadequate attention, and floods and droughts take an unnecessarily severe toll. One reason for this is that price signals that reflect scarcities of goods and thereby guide investments and resource allocation in the private sector are usually distorted or absent in decision-making relating to water. To aid in cost-benefit analysis under conditions where appropriate price incentives are absent, economists have developed a range of alternative or "non-market" methods for measuring economic benefits.

55. Zhang, Chuan-Mian, H. J. Morel-Seytoux, and R. A. Young, 1990. An approach to modeling a stream aquifer system for conjunctive management. Completion Report No. 170, 145 pp. Colorado Water Resources Research Institute; Colorado State University, Fort Collins, CO 80523 (USA).

Abstract: A general methodology for modeling a groundwater system with complex boundary conditions by using the discrete kernel approach is developed. This methodology is applied in modeling a stream-aquifer system where the stream-aquifer relationship is in permanent hydraulic connection. Based on the fact that the interaction flux between stream and aquifer, i.e., return flow, is proportional to the difference between water levels in the river and in the aquifer, the stream-aquifer system is modeled as a boundary-value problem with a time-dependent third type boundary, which, in definition, is a kind of boundary condition where a linear combination of the piezometric head and its normal derivative is prescribed. This stream-aquifer model includes two parts. The first part is a discrete kernel generator, which generates drawdown discrete kernels and return flow discrete kernels by a finite difference model for the case of homogeneous initial conditions and homogeneous boundary conditions of the third type. These discrete kernels are calculated only once and saved. They are the characteristic coefficients which represent the linear relationship between excitations and responses for a particular physical system. The second part is a simulator, which simulate the responses of the system due to any kind of activities imposed on the system, such as pumping, recharge, irrigation, non-equilibrium of the initial conditions and variation of river stages, in terms of the discrete kernels.