Integrated Management of Groundwater and Surface Water Resources: Investigation of Different Management Strategies and Testing in a Modeling Framework

Final Report

Fred L. Ogden, Ph.D., P.E., P.H., Professor, Department of Civil & Architectural Engineering, University of Wyoming, Laramie, WY 82071

Melinda Harm-Benson, J.D., Assistant Professor Department of Geography, University of New Mexico, Albuquerque, NM 87131

April 30, 2010

Executive Summary

The application of non-conjunctive prior-appropriation allocation strategies to groundwater resources has the potential to curtail water surface water availability. Predictive understanding of the interactions of groundwater wells with surface water rights for management purposes requires a model to ascertain the worth of different management strategies. The degree of impact of a management scheme for groundwater pumping will depend on aquifer properties, degree of connectedness between surface water and groundwater, pumping history and rates, recharge, projected demands on use, and the particular management strategy employed.

Methods: We performed a detailed investigation of groundwater-surface water management strategies used in Western states, and examined the implications of different management strategies on the water rights of surface and ground water water rights holders. A policy study was conducted in a legal framework that considered the application of different policies in other states as they relate specifically to Wyoming law. The *MODFLOW*-based Groundwater Management model (*GWM*), which simulates the effect of different groundwater pumping configurations on surface water depletions was set up an on the Bates Creek Irrigation District near Casper, Wyoming, an example modeling framework that can be used to to determine the impact of the different management strategies on surface and groundwater rights in a stream underlain by an alluvial aquifer.

Objectives: The objectives of this research project were to:

1) produce a complete list of existing viable potential strategies for conjunctive management of surface and groundwater rights in alluvial aquifers;
2) study of the effect of variables such as surface water flow rate, streambed conductivity, groundwater pumping rate per unit area, aquifer properties, distance of wells from stream, on the impact of each management strategy on the rights of surface and groundwater permitees; and,
3) transfer results to the State Engineer's office, and assist in interpreting policy and setting up the model in specific locations of interest to the State Engineer's Office.

Deliverables: Policy details and legal analysis pertaining to the management of conjunctive surface and ground waters within the prior-appropriation water rights doctrine. A contemporary modeling framework that can be used by the Wyoming Office of State Engineer to test conjunctive management strategies in specific areas of interest.

Table of Contents

1. Legal Analysis of Ground Water and Surface Water Conjunctive Management Within the Context of Wyoming Water Law

Melinda Harm Benson, J.D., Assistant Professor, Department of Geography,
University of New Mexico, Albuquerque, New Mexico, 87131

Kris Koski, Emilene Ostlind, and Jamie L. Wolf
University of Wyoming Ruckelshaus Institute of Environment and Natural Resources
Laramie, Wyoming, 82071

Introduction

This report summarizes a detailed investigation of groundwater-surface water management strategies (referred to here as "conjunctive management" used in several Western states. The research was based on the hypothesis that the application of allocation strategies to groundwater resources has the potential to curtail water groundwater availability and that the potential interactions with surface water rights requires a model to ascertain the value of different management strategies. The degree of impact of a management scheme for groundwater pumping depends on aquifer properties, degree of connectedness between surface water and groundwater, pumping history and rates, recharge, projected demands on use, and the particular management strategy employed.

This research comes at an important time in the development of conjunctive management strategies. Recently, both Wyoming and Idaho's conjunctive management approaches survived legal challenges. In both cases, however, questions remain regarding the implementation of those management strategies. In Idaho, the Supreme Court ruled that the state's conjunctive management regulations were "facially valid" under Idaho's prior appropriation doctrine but did not have an opportunity to rule on whether the State Engineer's application of the law as applied to a specific set of management decisions would survive scrutiny (*American Falls Reservoir District v. IDWR*, 2007). Similarly, a Wyoming district court recently upheld the State Engineer's decision to restrict groundwater users to meet surface use demands under the state's conjunctive management approach, but, for procedural reasons there was no appeal, and future legal challenges are likely (*Rivett v. Wyoming State Engineer's Office*, 2009).

In states where both the ground and surface waters are managed using a prior appropriation approach, conjunctive management may be necessary in order to protect senior appropriators with permits from both hydrological systems. The challenge becomes how to manage ground and surface waters conjunctively when there is limited hydrologic data regarding interconnectivity, forecasting of surface flows and groundwater recharge rates.

Methods

On the policy front, the research into relevant conjunctive management strategies was three-fold: (1) traditional legal research into the ground and surface water management strategies of Wyoming, Idaho, Colorado, Washington and Arizona; (2) primary interviews with state agency officials and other important individuals within the different jurisdictions; and (3) peer review of findings with key water experts in the field.

An investigation of the legal approaches of the selected states was conducted using relevant, statutes, regulations and case law. In addition, newspaper articles, peer-reviewed and gray literature was used, as appropriate, in order to assess the current state of conjunctive management in each state and identify examples of conjunctive management approaches and outcomes.

In addition, we conducted a series of semi-structured interviews of water experts in the selected states. Interviewees were assured anonymity and asked several questions designed to elicit their opinions of both the research findings conducted during the legal research phase of the project and their views of how management was occurring in their states (see Appendix "A"). Questions asked of the experts included:

> (1) What has been your experience with your state's attempt to conjunctively manage ground and surface water resources and/or address conflict between surface and ground water users? Would you describe the experience as positive, negative? Why or why not?
>
> (2) Do you have any suggestions for how your state could improve its management of ground and surface water use conflicts?
>
> (3) Can you provide any examples of specific ground and surface water interactions in your state that inform your answers to questions 1 and 2?
>
> (4) What, in your opinion, is the greatest barrier to effective conjunctive management in your state?
>
> (5) Do you feel like your state has the necessary technical/hydrologic information necessary to implement its management scheme? Why or why not? What would improve the situation?

The results of these interviews are included in the individual state summaries and are also summarized in the results and discussion section.

Wyoming

Wyoming Overview

According to Wyoming's Constitution, priority of appropriation for beneficial water uses is the guiding doctrine in Wyoming and it is to be administered by the Board of Control (Wyoming Constitution, Article 8 §§ 1-3). Any person seeking to appropriate groundwater must seek a permit from the State Engineer (Wyoming Statute § 41-3-930(a)). If the State Engineer determines that the surface and groundwater in a particular area constitutes "one source of supply," then both shall be administered under a single set of priorities (Wyoming Statute § 41-3-916). In order to administer groundwater supplies, the Board of Control may designate "control areas" if:

1) groundwater use exceeds, equals or is approaching the recharge rate;
2) conflicts between users are ongoing or foreseeable;
3) waste of water is or may be occurring; or
4) other conditions exist that require such designation (Wyoming Statute § 41-3-912).

Once a "control area" is established, the State Engineer is then authorized to adopt corrective controls (Wyoming Statute § 41-3-915). Such corrective controls that the State Engineer may institute include:

1) closing the control area to any new appropriations or instituting well-spacing regulations for new appropriations;
2) ordering junior groundwater users to cease withdrawals; or
3) determining the total withdrawal for a particular day, month or year and apportioning such withdrawal in respect to priority dates (Wyoming Statute § 41-3-915).

Wyoming Constitutional Provisions

Wyoming's State Constitution contains provisions relating to the management and distribution of water. As such, all legislative and agency statutes and regulations must conform to the guidelines set forth in the Wyoming Constitution. Article 8 Section 1 of the Wyoming Constitution declares that "[T]he water of all natural streams, springs and lakes…are property of the state" (Wyoming Constitution, Article 8 § 1). In other words, "water is the property of the state, under control by the state and held in trust for its people" (*Hunziker v. Knowlton*, 1958).

Article 8 Section 3 adopts the prior appropriation doctrine by stating: "[P]riority of appropriation for beneficial uses shall give the better right. No appropriations shall be denied except when such denial is demanded by the public's interest" (Wyoming Constitution, Article 8 § 3). Appropriable water is that water "which if not intercepted would naturally reach a stream" (*Bower v. Big Horn Cana*l, 1957). Percolating waters developed by excavations or other artificial means do not belong to the state, rather they belong to the owner of the land upon which they are developed.

Article 8 Section 2 establishes that "[T]here shall be a board of control, composed of the state engineer and superintendents of water divisions…which under such regulations have the supervision of the waters of the state and their appropriation, distribution and diversion" (Wyoming Constitution, Article 8 § 2).

Overall, the Wyoming State Constitution establishes:

1) any water, except such water that is defined to be percolating water, is property of the state held in trust for the people of the state;
2) priority of appropriation is the guiding doctrine of Wyoming water law;
3) water subject to appropriation is any water which would naturally reach a stream;
4) only beneficial uses of water may give rise to an appropriation;
5) an appropriation of water typically may not be denied if there is available water to appropriate; and
6) the Board of Control is responsible for regulating the appropriation, distribution and diversion of Wyoming's waters.

Wyoming Groundwater Management

Groundwater is defined as "any water, including hot water and geothermal steam, under the surface of the land or the bed of any stream, lake, reservoir, or other body of surface water, including water that has been exposed to the surface by an excavation" (Wyoming Statute § 41-3-901(a)(ii)). "Rights to underground water shall be subject to the same preferences as provided by law for surface users" (Wyoming Statute § 41-3-906). Therefore, underground water is appropriated similar to surface water and is also subject to beneficial use requirements.

Pursuant to Wyoming Statute § 41-3-905, "[N]o well shall be constructed…unless a permit has been obtained from the state engineer" (Wyoming Statute § 41-3-930(a)). Thus, any person seeking an appropriation of groundwater must file a groundwater application with the state engineer (Wyoming Statute § 41-3-905). Permits will typically be granted as a matter of course, unless the proposed well lies within a groundwater control area (Jacobs et al., 2003, p. 6).

"It is an express condition of each groundwater permit that the right of the appropriator does not include the right to have the water level or artesian pressure…maintained at any level or pressure higher than that required for maximum beneficial use of the water in the source of supply" (Wolfe et al., 1989). Since maximum beneficial use is a permit requirement, the appropriator is responsible for maintaining a well at an adequate depth with a sufficient pump.

A 'control area' is "any underground water district or sub-district that has been so designated by the Board of Control" (Wyoming Statute § 41-3-912). A control area may be designated where:

i. the use of underground water is approaching a use equal to the current recharge rate;
ii. groundwater levels are declining or have declined excessively;
iii. conflicts between users are occurring or are foreseeable;
iv. the waste of water is occurring or may occur; or
v. other conditions exist or may arise that require regulation for the protection of the public interest. (Wyoming Statute § 41-3-912)

Future groundwater permits in control areas are only granted if the state engineer finds that "there are inappropriate waters in the proposed source, that the proposed means of diversion or construction is adequate, that the location of the proposed well does not conflict with any well spacing or well distribution regulation, and that the proposed use would not be detrimental to the public interest" (Wyoming Statute § 41-3-932(c)).

The State Engineer is authorized to adopt corrective controls in control areas where it appears immediate regulation is necessary (Wyoming Statute § 41-3-915). In fact, the state engineer must hold a hearing on the necessity for and utilization of corrective controls if twenty appropriators or one-tenth of the appropriators in a control area petition for a hearing (Wyoming Statute § 41-3-915). After such hearing, the state engineer may adopt corrective controls (Wyoming Statute § 41-3-915). Corrective controls that the state engineer may order include:

i. closing the controlled area to any further appropriation of underground water;
ii. determining the permissible total withdrawal of underground water in the control area for each day, month or year and apportioning such total in accordance with the relative dates of priority of such rights;
iii. ordering junior appropriators to cease or reduce withdrawals;
iv. ordering a system of rotation of use of underground water if he finds that cessation or reduction by juniors will not result in proportionate benefits to senior appropriators; or
v. instituting well spacing requirements if permits are granted for new wells. (Wyoming Statute § 41-3-915)

"Appropriations of underground for stock or domestic use…shall have preferred right over rights of all other uses, regardless of their dates of priority" (Wyoming Statute § 41-3-907). A domestic use is defined as "household use including lawn and garden watering for non-commercial family use where the area to be irrigated does not exceed 1 acre" (Wyoming Statute § 41-3-907). The maximum quantity of water that can be pumped and qualify for the domestic use exception is 25 GPM (Wyoming Statute § 41-3-907).

Groundwater subject to appropriation is defined under Wyoming Statute § 41-3-901(a)(ii). A permit from the State Engineer is necessary for a groundwater appropriation. Groundwater permits will typically be granted unless the area where such permit is sought lies in a control area. (Figure 1) Control areas are designated by the Board of Control, when the Board of Control determines that conditions, delineated under Wyoming Statute § 41-3-912, exist. The state engineer must determine that there is unappropriated groundwater to issue new permits in control areas. The state engineer may adopt corrective controls in control areas. These corrective controls may include shutting off the wells of junior appropriators.

Wyoming: Conflict Between Surface and Groundwater Users

Wyoming Statute § 41-3-916 states, "[W]here underground waters in different aquifers are so interconnected as to constitute in fact one source of supply, or where underground waters and the waters of surface streams are so interconnected as to constitute in fact one source of supply, priorities of rights to the use of all such interconnected waters shall be correlated and such single schedule of priorities shall relate to the whole common water supply" (Wyoming Statute § 41-3-916). In fact, every groundwater permit includes an express condition that it may be subject to correlation with surface water rights if the ground and surface water are determined to be interconnected. Therefore, once the State Engineer determines that the underground and surface waters constitute "one source of supply," priority dates for both adhere to a single set of priorities. Thus, a common theme in Wyoming's water conflicts has been one of proving connectivity between ground and surface water sources and its effect on the enforcement of priority rights.

Figure 1: National Park Service.Teton Reflection in Beaver Pond. Retrieved July 16, 2009, from http://national-park.of-the-week.com/grand_teton.html

Wyoming Outcomes and Challenges: Rivett v. Wyoming State Engineer's Office

As has been true for each of the states examined in this study, Wyoming has experienced conflicts with management of surface and groundwater. The case in interest here was instigated in 2007 in Natrona County in central Wyoming and centered on the need burden of proving connectivity between surface and groundwater sources before priority curtailments can be ordered.

In spring of 2007 Mr. Charles Scott of the Bates Creek Cattle Company, a surface water user with a priority right dating to 1886, made a request for regulation to the local water Commissioner. The Commissioner subsequently ordered the shutdown for the rest of the summer of some wells that were located upstream of the Cattle Company's diversion from Bates Creek and junior in priority right. These included three wells owned by Dennis and Sherry Rivett, which they used for irrigation. The priority dates for the Rivetts' groundwater wells are 1976 and 1977.

The Rivetts appealed the curtailment order to the Superintendent of their water district. The Superintendent denied the appeal and the Rivetts appealed that decision to the State Engineer. The State Engineer sided with the Commissioner and the Superintendent to again deny the appeal, after which the Rivetts took the case to the 7th District Court in Wyoming by submitting a petition for review of the State Engineer's decision. The case rested in the court through the winter of 2007-08 with both the petitioners and the respondent, the State Engineer, submitting briefs.

Figure 2: Photo by Yingling, Rob (BighornMountains.com, LLC). Wind River Canyon. Retrieved June 30, 2009, http://www.bighornmountains.com/photo-gallery/thermopolis.htm

In spring of 2008 Mr. Sherman Drake, a surface water user with a right in the Bowie #1 Ditch dating to 1886, made a request for regulation to the water Commissioner similar to the request made by the Bates Creek Cattle Company the previous summer. Bowie #1 Ditch contains surface water diverted from Bates Creek at a headgate downstream from the Rivetts' and wells. Again, the Commissioner subsequently ordered the shutdown for the rest of the summer of several upstream wells including the same three Rivett wells and two wells owned by David and Jenise Whisler. The Whisler wells are used for irrigation and have priority dates of 1971. As had happened the previous year, both the Rivetts and the Whislers appealed to the water Superintendent, then to the State Engineer, and finally to the 7th District Court as each appeal was denied along the way.

The groundwater users claim that the orders to shut down their wells were unlawful and ask the District Court to reverse that order. The main arguments: 1) the State Engineer did not have substantial evidence to prove that withdrawals of groundwater from their wells was affecting the surface water users who issued the requests to have them regulated, and 2) the well owners were not given due notice or a chance to defend their water rights in a hearing before they were ordered to shut down.

In November 2008 the three cases—the Rivett case from 2007 and the Rivett and Whisler cases from 2008—were consolidated and assigned to a new judge in the district court as the original judge hadn't found time to work on the cases. A hearing was held in District Court for April 3, 2009, soon after which the court ruled in favor of the State Engineer's Office and upheld their management action.

During an oral ruling on April 22, 2009 that was later incorporated into a court order, the court stated: "the only evidence in the record establishes that when petitioners turn on their ground water wells, it has a direct, ultimately, impact on the surface water levels of Bates Creek. Given such evidence, this Court cannot conclude that the findings were inadequate." Due to a procedural error, appeal to the Wyoming Supreme Court was denied. As a result, it is likely that similar claims may be raised again in future litigation.

Figure 3: U.S. Geological Survey, North Platte River in Wyoming. Retrieved 26 April 2010, from http://wy.water.usgs.gov/projects/drought/images/

Wyoming Outcomes and Challenges for the Future

According to Wyoming state law, "where underground waters and the waters of surface streams are so interconnected as to constitute in fact one source of supply, priorities of rights to the use of all such interconnected waters shall be correlated and such single schedule of priorities shall relate to the whole common water supply. The state engineer may by order adopt any of the corrective controls specified in [the Wyoming statutes]."

On major challenge centers on who bears the burden of proofing the connectivity of ground and surface waters. "Whose responsibility is it to prove connectivity? In our study we said the water sources are connected," says one person interviewed at the SEO. "The groundwater users never proved they were not connected. They had that opportunity to refute our findings and they never did. On the back of our water rights it says that the water application is approved subject to the condition that the proposed use will not interfere with other water rights. Every water right carries a risk in that if it interferes with other existing water rights it can be revoked. People never realize that until it's too late. They get upset because their wells get shut down for two weeks and all the crops for the year die, but from the beginning each water right holder runs the risk of having their water curtailed. We're pretty clear with that up front that water right is at risk. We're trying to find a better management solution right now."

Idaho

Idaho Overview

Idaho's State Constitution specifically adopts the doctrine of prior appropriation. The Idaho Department of Water Resources (IDWR) is responsible for administering and developing regulations for the state's prior appropriation system (Raines, 1996). Any person seeking to appropriate groundwater must get a permit from IDWR (Raines, 1996) (Figure 4).

Figure 4: Photo by Carlson, Dave. South Fork of the Snake River above Heise, Idaho. Retrieved July 15, 2009, from http://www.idwr.idaho.gov/waterboard/WaterPlanning/CompBasinPlanning.htm

Idaho has adopted a comprehensive set of rules for the conjunctive management of surface and groundwater for "areas determined to have a common groundwater supply" (Idaho Administrative Procedure Act, Section 37). For these areas, the director of IDWR has the duty to respond to delivery calls made by senior surface or groundwater users against junior groundwater pumpers (Idaho Administrative Procedure Act, Section 37). The Conjunctive Management Rules apply when the senior water user is found to suffer material injury due to the pumping of junior groundwater users. The most important factor in determining whether there is material injury is whether the junior groundwater rights affect the quantity and timing of water available to a senior user or the cost of exercising the senior water right (Idaho Administrative Procedure Act, Section 37). However, the senior's available storage water and the extent to which the senior's water right could be met by employing alternative reasonable diversion means and conservation practices are factors to be considered in determining material injury. If material injury is found, the junior's pumping will be curtailed unless the junior has an approved mitigation plan (Idaho Administrative Procedure Act, Section 37). A mitigation plan "identifies actions and measures to prevent, or compensate holders of senior-priority water rights for, material injury caused by the diversion and use of water by the holders of junior-priority groundwater rights" (Idaho Administrative Procedure Act, Section 38.03.11.000.15).

Idaho Constitutional Provisions

Article XV of the Idaho Constitution is dedicated entirely to water rights. According to Article XV § 3, the use of water is declared a public right and "the right to divert and appropriate the unappropriated waters of any natural stream to beneficial uses shall not be denied." Furthermore the appropriation doctrine is the guiding principle as "[P]riority of appropriation shall give the better right as between those using the water" (Idaho Constitution, Article XV, § 3).

Idaho Groundwater Management

IDWR is responsible for administering and developing rules and regulations for both surface and groundwater under the state's prior appropriation system (Raines, 1996). The director of IDWR supervises water distribution within each district, while the district water masters distribute water according to priority and shut off headgates in times of scarcity (Idaho Code § 42-604).

Idaho requires permits to appropriate groundwater (Idaho Code § 42-202). Any person seeking a permit to pump groundwater must apply to IDWR before commencing construction. Wells used for domestic purposes do not require a permit provided that the drilling is authorized by a license and subject to inspection by IDWR and the Idaho Department of Environmental Quality (IDEQ) (Idaho Code § 42-202).

Conjunctive management rules apply to "areas determined to have a common groundwater supply" (Idaho Administrative Procedures Act, Section 37). The "rules apply to all situations where the diversion and use of water under junior-priority groundwater rights either individually or collectively causes material injury to uses of water under senior-priority water rights … The rules acknowledge all elements of the prior appropriation doctrine as established by Idaho law" (Idaho Administrative Procedures Act, Section 37).

The conjunctive management rules describe IDWR's procedures for responding to a water delivery call made by a senior surface or groundwater user against a junior groundwater user (Kray, 1996). In order to initiate a delivery call, a senior water user must file a petition that includes: a description of the senior's water right, names and addresses of the groundwater users who are alleged to cause material injury and any data or information to support the claim of material injury (Idaho Administrative Procedures Act, Section 37). If material injury is found, the director must "regulate the diversion and use of water in accordance with the priorities of rights of the various surface or groundwater users," but the director may lessen the economic impact by declining immediate and complete curtailment if the material injury is long range or delayed (Idaho Administrative Procedures Act, Section 37)(figure 2).

Rule 42 lists factors that the director may consider in determining whether the senior has suffered material injury and whether the senior is utilizing his water right without waste (Idaho Administrative Procedures Act, Section 37). Of importance is "[W]hether the exercise of junior-priority groundwater rights individually or collectively affects the quantity and timing of when water is available to, and the cost of exercising, a senior-priority surface or groundwater right" (Idaho Administrative Procedures Act, Section 37). However, among the factors to be considered are the extent to which the senior's water right could be met by employing reasonable diversion and conveyance efficiency and conservation practices and the extent to which the senior's water right could be met using an alternate reasonable means of diversion, including the construction of wells (Idaho Administrative Procedures Act, Section 37). Factor (g) of conjunctive management Rule 42.01 allows the director to consider the senior's available storage water in determining whether the senior has suffered material injury (Idaho Administrative Procedures Act, Section 37).

Figure 5: Photo by High, Jac, (Go Northwest, Inc.). Shoshone Falls on Snake River, Twin Falls, ID. Retreived April 26, 2010 from: http://www.gonorthwest.com/Idaho/southcentral/idsc.htm.

Rule 40 permits junior-priority users to maintain their groundwater pumping if they have an approved mitigation plan (Idaho Administrative Procedures Act, Section 37). A mitigation is "[A] document submitted by the holder(s) of a junior-priority groundwater right and approved by the director as provided in Rule 043 that identifies actions and measures to prevent, or compensate holders of senior-priority water rights for, material injury caused by the diversion and use of water by the holders of junior-priority groundwater rights within an area having a common groundwater supply" (Idaho Administrative Procedures Act, Section 37). Rule 43 lists the procedures to be followed and the factors to be considered in approving a junior's mitigation plan. Of importance is "whether the mitigation plan will provide replacement water, at the time and place required by the senior-priority water right, sufficient to offset the depletive effect of groundwater withdrawal on the water available in the surface or groundwater source at such time and place as necessary to satisfy the rights of diversion from the surface or groundwater source" (Idaho Administrative Procedures Act, Section 37). However, "consideration will be given to the history and seasonal availability of water for diversion so as not to require replacement water at times when the surface water right historically has not received a full supply, such as during annual low-flow periods and extended drought periods" (Idaho Administrative Procedures Act, Section 37).

Idaho: Conflict between Surface and Groundwater Users

Until 1994, IDWR issued permits for groundwater pumping, regardless of the effects upon surface users (Idaho Code § 42-202). However, the Idaho Supreme Court case of *Musser v. Higginson* caused IDWR to change its groundwater management rules and policies. In Musser, the court held that the failure to deliver water, due to interfering groundwater pumping, to the senior surface user was arbitrary and capricious under Idaho Code § 42-602 (*Musser v. Higginson*, 1994). Following Musser, IDWR adopted the most comprehensive set of conjunctive management rules of any state. These rules were subsequently found to be facially constitutional in the Idaho Supreme Court case *American Falls Reservoir District v. Idaho Department of Water Resources* (March 2007).

In *American Falls*, the Idaho Supreme Court clarified that the director should have some discretion to determine whether the carryover water is reasonably necessary for future needs. The court reasoned that "first in time" is subject to beneficial use and to permit excessive carryover water would be in itself unconstitutional (*American Falls Reservoir District v. IDWR*, 2007).

Idaho: Outcomes and Challenges

In the winter of 2005, Idaho water users steeled themselves for what would be the 6th year of a drought that had diminished water throughout the West. The state had experienced below-average precipitation, and reservoirs had been drawn down from average levels over the preceding drought years (U.S. Water News Online, 2005a). Especially hard hit were senior surface water users in the Snake River watershed of south-central Idaho (Figure 6).

Though wetter weather was on the forecast, Idaho water users did not relax. They knew that even if rainfall levels returned to normal, water sources in the state could take years to replenish. In addition, no one knew if the drought would break, or if it was one of the first signs of irreversible climate change (U.S. Water News Online, 2005b). Around the state, lack of water forced agriculturalists to reduce livestock numbers and farmers to cultivate only a fraction of their lands (U.S. Water News Online, 2005b; U.S. Water News Online, 2004). Surface waters were the first to diminish, while groundwater users continued to pump normal amounts of water out of the underground aquifers (Associated Press, 2001).

In response to junior groundwater rights users accessing pumped water for irrigation while the surface rivers dried up, seven south-central senior rights holders formed the Surface Water Coalition (SWC). The coalition members include the A & B Irrigation District, American Falls Reservoir District No. 2, Burley Irrigation District, Milner Irrigation District, Minidoka Irrigation District, North Side Canal Company, and Twin Falls Canal Company (U.S. Water News Online, 2007a). The latter is the largest canal company in the state. In 2005, the SWC took two actions to force the IDWR to provide them with water.

Figure 6: U.S. Geological Survey (modified). (1992). The Snake River Plain Regional Aquifer System. Retrieved 25 April, 2010, from http://pubs.usgs.gov/ha/ha730/ch_h/H-text8.html

First, in January 2005 the SWC claimed that groundwater users were sucking up their constitutionally given water and called on the IDWR to fulfill their senior rights by curtailing junior groundwater use so that surface water sources could recharge (Snyder, 2006a). Upset at the prospect of providing water for recharge in a time of shortage, groundwater users questioned whether surface users had actually suffered any material injury to their water rights (Dunlop, 2006). Proving "injury" is central to Idaho's conjunctive management laws, and must be established before a call for curtailment by junior water users can be answered. The director of the IDWR agreed that the surface water users had suffered injury, which he calculated to be 133,400 acre-feet of water in 2005. The IDWR ordered groundwater users to come up with the first 27,700 acre-feet of replacement water during the 2005 season (Dunlop, 2005).

The surface water users, upset that IDWR was not partitioning them as much water as they felt they deserved under their prior appropriation rights, responded by arguing that the conjunctive management rules requiring them to prove they were experiencing material injury were unconstitutional. In August of 2005 five members of the SWC—the American Falls Reservoir District No. 2, A & B Irrigation District, Burley Irrigation District, Minidoka Irrigation District and the Twin Falls Canal Co. —sued the IDWR about the constitutionality of conjunctive management (Dunlop, 2005).

Groundwater rights holders argued that the conjunctive management rules had already been established by the state government and should be upheld. Meanwhile, a representative of the SWC called the conjunctive management rules "bogus" and argued that when those rules were created, the senior surface rights holders "got short shrift in that deal" (Pence, 2005).

In June of 2006, the district judge ruled in favor of the surface water users, agreeing that indeed conjunctive management did violate the state of Idaho's constitutionally mandated prior appropriation. Groundwater users and the state of Idaho (via the IDWR) appealed the case to the state Supreme Court, which heard the case in December of 2006. At this hearing, which was referred to as Idaho's, "most important water-rights case in two decades," the Court argued that, "water would not be used for the public good if senior water-users [were] allowed to potentially hoard water that could be put to better use if allocated to junior users" (Environment and Energy Publishing, LLC, 2006).

The hearings continued through the winter until, on March 5, 2007, the Idaho Supreme Court granted the IDWR, "discretion in allocating water resources, rather than going solely by first-come, first-served water rights. The court ruled in favor of the state's contention that its conjunctive water management policy, which conflicts with the state's prior allocation doctrine, is constitutional"

(Environment and Energy Publishing, LLC, 2007). The state decided that even those with senior water rights must have limits on what they can access in times of drought. Those limits are up to the determination of the IDWR and must be connected to reasonable and beneficial uses of the water.

Surface water rights holders considered the decision a "deflating loss" (Times-News editorial board, 2007). They complained of delays associated with conjunctive management, including, "the burden of proof that saddles senior users far beyond that of junior users, and the lack of any time frame to settle water calls in a water season" (Times-News editorial board, 2007). Meanwhile, groundwater users were relieved that the state upheld the conjunctive management rules, essentially protecting them from having to give up too much water to the surface users. However, the SWC's 2005 call for curtailment was still standing, requiring that groundwater pumpers divert water to senior users.

The state Supreme Court may have answered questions about the rules for managing water in Idaho, but the burden of deciding how much water to release or curtail when and where still rested in the hands of the IDWR who quickly set to work planning distribution of the little water in the state. Just a few short months after the Supreme Court decision, the IDWR picked up calls for groundwater curtailment that had been issued in 2005 by Blue Lakes Trout Farm and Clear Springs Food's Snake River Farm (U.S. Water News Online, 2007b). The IDWR threatened to curtail groundwater pumping unless mitigation could be achieved (U.S. Water News Online, 2007b). In the past, groundwater users had avoided curtailment orders by voluntarily sending some of the water they pumped from the ground into surface water sources. In this case, however, the low snowpack and forecasted drought had put water at such a shortage that groundwater users could not afford to send it away (U.S. Water News Online, 2007b). At the last moment, groundwater users avoided the curtailment by leasing water through the IDWR from water rights holders below Milner Dam and exchanging the leased water for release from reservoirs (Idaho Water Resource Board, 2005).

As water shortages continue, groundwater users are unhappy about the amount of water they are asked to give up, while surface water users are unhappy because they are not getting enough water to conduct their own agriculture or maintain trout farms. In light of these conflicts, litigation has continued. As each year goes by water levels in the state's aquifers have gone down, increasing the risk of curtailment for groundwater pumpers. Meanwhile, IDWR continues to encourage mitigation and collaboration, hoping to avoid curtailment altogether (Poppino, 2008). One way for groundwater users to mitigate is to join the Idaho Ground Water Appropriators. This allows all groundwater users to work as a group to find money and water sources to pay back the water they take from the aquifer. As long as the water is replaced, they will not be curtailed (Poppino, 2008).

Just last October, IDWR issued a curtailment warning for the Eastern Snake Plains Aquifer in south-central Idaho for the summer of 2009. The warning is a response to calls from Clear Springs Foods, Inc. (which raises fish at a Snake River Farm facility), Blue Lakes Trout Farm, Inc., and the SWC, all three of whom hold senior water rights (Otter & Tuthill, 2008). To avoid this curtailment, groundwater users must cross their fingers for a large snowpack or seek out some new kind of mitigation to replenish any water they hope to withdraw over the coming year. One thing that both ground and surface water rights holders have agreed on is that they would like to see the aquifer replenished to original levels (Dunlop, Idaho water, 2005). In 2007, IDWR developed plans that would call for diverting nearly 30,000 acre feet of water from the Snake River into a network of channels in the hope that the water would seep through the channel beds and filter into and raise the level of the aquifer (U.S. Water News Online, 2007c). Indeed, when flow rates were measured that October, engineers found that water quantities diminished as measurements were taken farther downstream indicating that was water seeping out of the canals (Christensen, 2007). What they still don't know, however, is whether the water for sure reached the aquifer, and if so, how long it would take to flow through the aquifer and show up at other sites where it will again be available to surface water users (Christensen, 2007).

Idaho: Challenges for the Future

In 2008 the State Legislature created a Comprehensive Aquifer Planning and Management Program (CAMP) and an Aquifer Planning and Management Fund (Idaho Department of Water Resources, 2009). In light of declining aquifer levels, reduced spring and river flows, and a number of lawsuits, the IDWR created an Eastern Snake Plain Aquifer (ESPA) (Figure 7) Advisory Board in 2008 to draft a plan. The plan marks an effort to adjust water supply and demand in the ESPA over the long term and to identify opportunities to manage the available water to meet current and future water needs (Berg, 2008). With large budgets, long-term working timeframes, and collaborative management practices, water users in Idaho hope that these programs will help rejuvenate the diminishing aquifers of the state, in turn replenishing the cold-water springs that feed the surface water sources (Berg, 2008).

Figure 7: U.S. Geological Survey. Discharge of the Eastern Snake River Plain aquifer from basalt cliffs above the Snake River gorge. Retrieved June 16, 2009, from http://water.usgs.gov/lab/chlorofluorocarbons/research/snake_river/.

Colorado

Colorado Overview

Colorado adheres to the doctrine of prior appropriation for both surface and groundwater. Specifically, groundwater management is dependent upon whether the groundwater lies within a non-designated, designated or Denver groundwater basin. In "non-designated groundwater basins" there is a rebuttable presumption that the groundwater is "tributary," such that surface and groundwater adheres to a single set of priorities. (Colorado Revised Statutes § 37-92-102, 2008). In "designated groundwater basins," groundwater withdrawal permits are issued if there is still unappropriated and such new appropriation will not cause impairment (*Fundingsland v. Colorado Ground Water Commission*, 1970). Finally, in "Denver groundwater basins," groundwater withdrawal permits are only approved for overlying owners contingent upon the requirement that no more than 1% of the underlying water may be extracted in any given year (Colo. Rev. Statute § 37-90-137(4), 2008)(Figure 8).

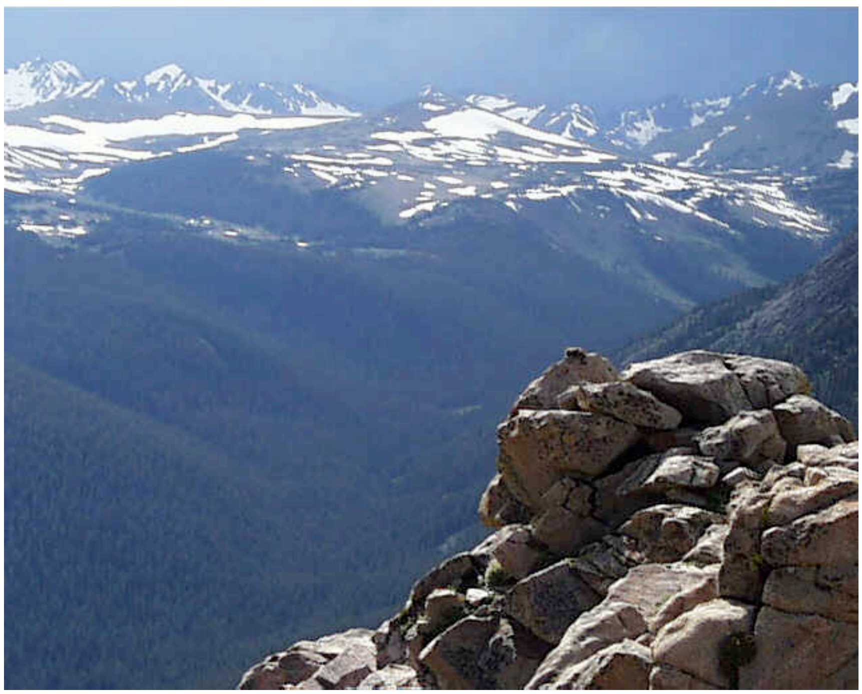

Figure 8: U.S. Fish and Wildlife Service, Rocky Mountain National Park. Retrieved April 26, 2010 from http://www.fws.gov/ficmnew/Proceedings%20on%20the%20Web/photo_gallery.htm

Colorado Constitutional Provisions

Article XVI § 5 of the Colorado constitution declares that (Figure 9) "water of every natural stream is…property of the public subject to appropriation." Article XVI § 6 states that "the right to divert unappropriated waters of any natural stream to beneficial uses shall never be denied" and "priority of appropriation shall give the better right," except that "water for domestic purposes" shall have preference. Thus, Colorado is a priority of appropriation state according to its Constitution.

Colorado Groundwater Management

The doctrine of prior appropriation applies to both ground and surface water in Colorado. Groundwater is defined as "any water not visible on the surface of the ground under natural conditions" (Colorado Revised Statute § 37-90-103(19), 2008). The Water Right Determination and Administration Act of 1969 (hereafter referred to as "the 1969 Act") furthered the oversight of groundwater use by creating water divisions, each encompassing a major river watershed Colorado Judicial Department). Each division has its own water court, which is part of the state judicial system and determines all water rights, administers the buying and selling of water rights, and otherwise oversees the use and distribution of water (Colorado Judicial Department). The water court includes a division engineer overseen by the State Engineer and a water judge assigned by the state Supreme Court (Colorado Judicial Department). Groundwater regulation in Colorado largely depends upon whether the groundwater is located in a non-designated, designated or Denver groundwater basin.

In non-designated groundwater basins, groundwater that is "tributary water" is administered under a single set of priorities with surface water (Colorado Revised Statute § 37-92-102, 2008). All groundwater in non-designated basins is presumed to be "tributary" (Bryner and Purcell, 2003). However, this presumption may be rebutted if the water is determined to be "non-tributary groundwater" (Bryner and Purcell, 2003). "Non-tributary groundwater" is groundwater that will not deplete the surface flow at a rate of 0.1% or less than the rate of groundwater withdrawal (Colorado Revised Statute § 37-90-103(10.5), 2008). For example, if a potential groundwater user wishes to extract 1000 gallons per minute (gpm), then in order for that groundwater to be considered non-tributary, the groundwater user must prove that the surface flow will be depleted by no more than 1 gpm.

If the groundwater is "tributary water," then the state engineer issues permits for new wells and regulates extraction according to the priority system (Bryner and Purcell, 2003). In order for the permit to be approved, the applicant must show that there is still unappropriated water available and that he will put the water to a beneficial use (Bryner and Purcell, 2003). Water courts have jurisdiction over both surface and tributary groundwater (Bryner and Purcell, 2003).

If the groundwater is "non-tributary groundwater," then priority of appropriation does not apply (Colorado Revised Statute § 37-90-102(2), 2008). Rather, the resource is allocated based upon ownership of the overlying land (Colorado Revised Statute § 37-90-102(2), 2008). "Economic development of (non-tributary groundwater) shall allow for reduction of hydrostatic levels and aquifer water levels" (Colorado Revised Statute § 37-90-102(2), 2008). Rights may be decreed by water courts based upon a hundred-year aquifer life, overlying land ownership and withdrawal rates not to exceed 1% per year (Colorado Revised Statute § 37-90-137(4), 2008). The state engineer issues permits for "non-tributary" wells and a permit is required before drilling.

Colorado has "designated groundwater basins," wherein "groundwater withdrawals have constituted the principal water usage for at least fifteen years preceding such proposed designation" (Colorado Revised Statute § 37-90-103(6)(a), 2008). The Groundwater Commission has jurisdiction over these basins and any person wishing to appropriate these waters must seek a permit from the commission (Colorado Revised Statute § 37-90-107(1), 2008). In these basins, permits are granted if there is still unappropriated water and the proposed well will not create "impairment" (*Fundingsland v.*

Colorado Ground Water Commission, 1970). What constitutes "impairment" is defined by the applicable designated groundwater basin (Colorado Code Regulations § 402-4, 2008). However, a permit that does not meet the guidelines of the designated groundwater basin may still be approved if there is a "replacement plan" (Colorado Revised Statute § 37-90-103(12.7), 2008).

"Not Non-Tributary Groundwater" is water in the Dawson, Denver, Arapahoe and Laramie-Fox Hills aquifers that fails to satisfy the definition of "Non-Tributary Groundwater (Colorado Revised Statute § 37-90-103(10.5), 2008)." Permits to appropriate these waters are issued by the water courts. These permits must include augmentation plans that, if needed, provide replacement water in order to prevent injury to senior water users (Bryner and Purcell, 2003). Overlying owners may withdraw groundwater from these aquifers and annual withdrawals may not exceed 1% of the available water underneath the owned land (Colorado Revised Statute § 37-90-137(4), 2008).

Colorado: Conflict between Surface and Groundwater Users

The most telling example of Colorado's issues with conjunctive management of surface and groundwater is set in the South Platte River Basin in the northeast corner of the state. Conjunctive water management was implemented in Colorado in a series of legislation passed in the 1960s and 70s. For the first time, the Colorado Ground Water Management Act of 1965 required groundwater users to apply to the State Engineer for a permit before drilling a well (Colorado Division of Water Resources (CDWR), 2007). Permitted wells were not subject to the priority rules that distribute surface water, but the State Engineer could deny a drilling permit if no unappropriated water was available or if drilling the well would cause material injury to senior water rights holders (Colorado Division of Water Resources, 2007). In 1968 two different studies both found that declining stream flows could be attributed to groundwater wells taking water over the preceding decade (Colorado Division of Water Resources, 2007).

Colorado: Outcomes and Challenges

The Water Right Determination and Administration Act of 1969 (hereafter referred to as "the 1969 Act") furthered the oversight of groundwater use by creating water divisions, each encompassing a major river watershed (Colorado Judicial Department). Division #1, the South Platte Water Division covers the northeast quarter of Colorado from the continental divide to the Nebraska/Kansas border and from the Wyoming border extending south past Denver (Wolfe, 2007)(Figure 9).

The 1969 Act called for an adjudication of all groundwater wells to be completed by the water courts before 1972. The adjudication would compile the information needed to determine priority of existing wells, so that groundwater could be entered into the prior appropriation system and the water courts could administer its distribution (Colorado Division of Water Resources, 2007). This met with much resistance from groundwater users because they had the most junior rights in the priority system and would be subject to water calls from senior rights holders. The 1969 Act allowed junior groundwater users to continue to pump water during a call as long as they filed a water-court-approved augmentation plan (Colorado Division of Water Resources, 2007).

Figure 9: U.S. Geological Survey. South Platte River Basin. Retrieved 26 April 2010 from: http://co.water.usgs.gov/nawqa/splt

In the South Platte River Basin an augmentation plan is, "a plan that acknowledges and quantifies depletions caused by well pumping, identifies sources of water that can be used to compensate for the out-of-priority depletions caused by well pumping, and outlines an approach to use the replacement water to replace out-of-priority depletions to the stream such that no other water right is injured" (Colorado Division of Water Resources, 2008).

In the 1970s, the State Engineer encouraged groundwater users to form coalitions, reasoning that large groups could more easily acquire funds and water for augmentation (Colorado Division of Water Resources, 2007). Two main coalitions were formed in the South Platte Water Division: Groundwater Appropriators of the South Platte (GASP) and Central Colorado Water Conservancy District's Groundwater Management Subdistrict (Central GMS) (Colorado Division of Water Resources, 2007). GASP and Central GMS submitted annual substitute water supply plans (SWSPs) to the State Engineer outlining how they planned to augment any water draw downs that could injure senior rights holders. The SWSPs were temporary versions of the more permanent "augmentation plans" described in the 1969 Act.

Everything went well for about 3 decades as water was abundant. Calls only occurred in late summer, if ever, and were easily augmented. The State Engineer continued to approve SWSPs submitted by the groundwater coalitions in the South Platte River Basin. In the 90s the State Engineer wrote to GASP and Central GMS that they should stockpile water in preparation for a possible drought (Colorado Division of Water Resources, 2007). GASP did not respond to the warning while Central GMS, which had a larger revenue base, did heed the Engineer's warning and saved some water.

In 2002, two important things happened that disrupted the smooth functioning of the water distribution system in the South Platte Water Division. First, an argument in the district civil court about land access turned into a dispute over water, and both the district water court, and later the state Supreme Court found the State Engineer had no judicial authority to approve the temporary SWSPs in place of water-court-approved augmentation plans as he had done for the past thirty years (Colorado Division of Water Resources, 2007). Instead, well organizations in the South Platte Water Division were given three years to submit augmentation plans to the water court (Colorado Division of Water Resources, 2007). The State Engineer could continue to approve or deny SWSPs as long as they were attached to augmentation plans under review by the water courts (Colorado Division of Water Resources, 2007). Second, Colorado experienced the worst drought year on record, causing a severe shortage of water among surface and groundwater users in the South Platte Water Division (Colorado Division of Water Resources, 2007).

In the face of the water shortage, controversy flared up. Senior surface water rights holders made calls early in the summer that lasted the rest of the year and continued through the following years. When GASP was unable to catch up on its augmentation, its SWSP for 2003 was not approved and the approximately 3,000 wells were not allowed to pump. GASP went out of business while Central GMS could barely lease enough water to fulfill its SWSP. Eventually a new groundwater coalition, the Well Augmentation Subdistrict (WAS) was formed out of members of GASP and other groundwater pumpers. WAS and Central GMS both compiled augmentation plans and submitted them to the water court in 2003 (Colorado Division of Water Resources, 2008).

While these augmentation plans were under review, the SWSPs for WAS in 2004, 2005, and 2006 were approved by the State Engineer. However, senior water rights holders appealed those SWSPs in spring of 2006 and the courts found they had indeed provided inadequate augmentation for the water they were using (Simpson, 2006). Snowpack was below average, and water that had been used for augmentation in the past was no longer available as it had been diverted to other uses (Simpson, 2006). By the summer of 2006, the 449 WAS wells were ordered not to pump until further notice (Simpson, 2006). These cases are still under review in the courts, and the last two summers have seen severe pumping restrictions that have been detrimental to agriculture in the South Platte River Basin. For example, the 2006 pumping curtailments resulted in loss of agriculture from 30,000 productive acres (Howe, 2008). At the same time, "the South Platte River had a shortage of about 15,000 acre-feet of water due to the delayed effect of Central WAS wells having pumped water in previous years under augmentation plans approved by the State Engineer" (City of Boulder, 2008).

Colorado Outcomes and Challenges for the Future

The conflict over conjunctive management in the South Platte River Basin raises two main issues surrounding water users' avoidance of the Colorado water court system. First of all, groundwater coalitions avoided adjudication by the water court by filing annual SWSPs with the State Engineer rather than applying for augmentation plans. This turned into a disaster when drought hit and the State Engineer continued to approve SWSPs that offered inadequate augmentation (City of Boulder, 2006). Now the South Platte River Basin is in a situation where hundreds of wells are ordered not to pump, downstream users are not finding as much water as they should in the river, and, as the calls of downstream senior rights climb higher through the appropriation system, municipalities like Boulder are having to give up water because the pumpers are unable to do so (City of Boulder, 2008). This problem has been addressed by the courts denying the State Engineer the authority to approve SWSPs.

The second, yet related, problem is that the exchange of water rights is stymied by having to pass through the water court, thus preventing efficient allocation of water in the South Platte River Basin (Howe, 2008). The way prior appropriation and water rights are supposed to work is that the senior rights get traded in a market to the highest value uses. (Figure 10) In the South Platte River Basin, the cities of Boulder, Greeley, and Highlands Ranch are considered higher value uses than agriculture and hold rights that are senior to agriculture supplied by pumping, but junior to downstream agricultural uses (Howe, 2008).

Figure 10: South Platte River, Weld County, Colorado. Retreived 26 April 2010 from: http://photokayak.fit2paddle.com/south-platte-river/

Charles Howe, Emeritus Professor of Economics at the University of Colorado, Boulder, and a team member of Western Water Assessment, argues for a water bank system to ameliorate this second problem. He writes, “In most western states, ‘water banks’ are being used to facilitate leases and permanent transfers [of water rights]. These programs, administered by each state, serve as clearinghouses or brokers, connecting buyers and sellers. … Greater use of the several forms of water banks will significantly reduce the ongoing conflicts between the traditional administration of water rights and the emerging need for greater flexibility and economic efficiency in western water administration” (Howe, 2008).

Washington

Washington Overview

In Washington, both surface and groundwater are subject to the doctrine of priority appropriation. Any person seeking to appropriate either surface or groundwater must seek a permit from the Washington Department of Ecology, unless an exception under Wash. Rev. Code § 90.44.050 applies (Revised Code of Washington § 90.44.050, 2008). If WDE determines that there is a "hydraulic continuity" between ground and surface water, then such waters must be managed under a single set of priorities (Washington Administrative Code § 173-549-060, 2008). A "hydraulic continuity" exists when groundwater withdrawal has at least a de minimis effect on surface water flow (*Postema v. PCHB*, 2000). No actual effect need be measured through standard measuring equipment; rather WDE may determine "hydraulic continuity" through acceptable scientific methods such as three-dimensional computer modeling (*Postema v. PCHB*, 2000). (Figure 11)

Figure 11: Washington Rivers Map from Geology.com. Retrieved 26 April, 2010 from http://geology.com/state-map/washington.shtml

Washington Constitutional Provisions

There is only one constitutional provision related to water in Washington's Constitution. Article XXI Section 1 states that "the use of the waters of this state for irrigation, mining, and manufacturing purposes shall be deemed a public use" (Washington Constitution, Article 21 § 1). Thus, Washington's State Constitution provides no guidelines to how water, determined to be a public use, should be managed and regulated.

Washington Groundwater Management

In Washington, both ground and surface waters are subject to the doctrine of prior appropriation. Accordingly, groundwaters in Washington "belong to the public and are subject to appropriation for beneficial uses" (Revised Code of Washington § 90.44.040, 2008). Groundwater is defined as "all waters that exist beneath the land surface or beneath the bed of any stream, lake or reservoir…whatever may be the geological formation or structure in which such water stands or flows, percolates or otherwise moves (Revised Code of Washington § 90.44.035(3), 2008)."

A permit is required to appropriate both ground and surface water. Potential appropriators must file a permit application with the Washington Department of Ecology (WDE) (Revised Code of Washington § 90.44.050, 2008). However, no withdrawal permit is necessary for stock-watering, watering of a lawn or non-commercial garden not exceeding one-half acres, domestic uses not exceeding 5,000 gallons per day and industrial purposes not exceeding 5,000 gallons per day (Revised Code of Washington § 90.44.050, 2008). Applications for permits must meet all the requirements of the surface water statute, Revised Code of Washington § 90.03.25 (2008), as well as the requirements of the groundwater statute, Revised Code of Washington § 90.44.060 (2008). If the WDE determines that there is water available for appropriation, such appropriation is for a beneficial use and such appropriation will not impair existing rights, then the application for permit is granted (Revised Code of Washington § 90.44.290, 2008).

WDE has the authority and discretion to limit withdrawals in a particular groundwater basin "to an amount that will maintain and provide a safe sustaining yield" (Revised Code of Washington § 90.44.130, 2008). If the total available withdrawal supply is "inadequate for the current needs of all holders of valid rights," "such decrease shall conform to the priority of the existing rights" (Revised Code of Washington § 90.44.180, 2008).

Washington's groundwater code recognizes the potential interconnectivity of ground and surface waters (Revised Code of Washington § 90.44.030, 2008). As such, when ground and surface waters are determined to be to be in "significant hydraulic continuity," both the ground and surface water rights must fall under one appropriation scheme (Washington Administrative Code § 173-549-060, 2008; *Rettkowski v. Department of Ecology*, 1993). (Figure 12) "Significant hydraulic continuity" exists if the WDE determines that a proposed or existing groundwater withdrawal has or will have "a direct and measurable impact on stream flows" (Washington Administrative Code § 173-510-050, 2008). In determining whether there is a "direct and measurable impact," any de minimis impact on the surface flow is sufficient (Washington Administrative Code § 173-510-050, 2008). Furthermore, WDE does not need to show an actual decrease in surface flow by groundwater pumping through standard measuring devices; rather, WDE may "use new information and scientific methodology as it becomes available and scientifically acceptable for determining hydraulic continuity" (Washington Administrative Code § 173-510-050, 2008). Currently, WDE maintains that a three-dimensional computer model is the best method for determining hydraulic continuity (Washington Administrative Code § 173-510-050, 2008).

Washington recognizes minimum stream flows. These flows were established by WDE, pursuant to the Water Resources Act of 1971, Wash. Rev. Code § 90.54.040 (2008). These minimum flows constitute an appropriation with a priority date of the effective date of the rule establishing such minimum flow (Revised Code of Washington § 90.03.345, 2008).

Figure 12: Camas Washougal Chamber of Commerse. The Columbia River Gorge National Scenic Area. Retreived 26 April 2010 from http://www.cwchamber.com/cwdata/Portals/0/thegorge.jpg

Thus, in determining whether to approve a permit to withdrawal groundwater, WDE must determine whether established minimum flows would be affected by the proposed use (Revised Code of Washington § 90.03.290, 2008). If the answer is yes, then the application must be denied.

In summation, WDE must adhere to a single set of appropriation dates for ground and surface waters if it determines that groundwater pumping will decrease the surface flow, even if that diminishment is de minimis. WDE can use acceptable scientific methods for determining ground and surface water interconnectivity and currently it utilizes a 3-d computer model. Any application to withdraw groundwater that will impair existing surface or groundwater rights or reduce minimum flows must be denied.

Washington: Conflict between Surface and Groundwater Users

Three cases that took place in the 1990s and early 2000s in Washington highlight the strengths and weaknesses with the state's water management system and provides context for issues Washington water users struggle to overcome today: *Rettkowski v. Department of Ecology* (1993), *Hubbard v. State of Washington* (1997), and *Postema v. Pollution Control Hearings Board* (2000). Each of these cases dealt with questions of defining connectivity between ground and surface waters and clarifying how to distribute the water to different rights holders.[1]

Washington's surface water code was written in 1917 and distributes water according to prior appropriation. The Groundwater Code of 1945 was meant to supplement the Surface Water Code and incorporate groundwater into the prior appropriation system. Importantly, the Groundwater Code says that new permits for water withdrawal are not allowed if they will impair existing surface water rights.

Washington: Outcomes and Challenges

A number of legal challenges over water management in Washington provide several examples

---

1 According to one person interviewed, in Washington, the term "conjunctive management" refers to a water supply utility that owns both surface and groundwater resources and manages them together for maximum efficiency by withdrawing surface water during wet periods and groundwater during dry periods. There is not a single term used to refer to the state's management of ground and surface waters together under one appropriation system. Rather, the state refers to "connectivity" or "continuity" between ground and surface waters

of the challenges associated with managing surface and groundwater resources.

Rettkowski v. Department of Ecology

Surface water rights in the Sinking Creek Basin of eastern Washington's Lincoln County are about 80 years senior to the first groundwater permits, which were issued in the 1950s (*Rettkowski v. Dept. of Ecology*, 1993). Starting in the 1960s, ranchers in Lincoln County who used surface water from Sinking Creek to water their livestock complained that irrigators were diminishing surface water supplies by pumping groundwater (*Rettkowski v. Dept. of Ecology*, 1993). Ecology eventually responded to the ranchers' concerns by conducting two studies, both of which found that the withdrawal of groundwater was negatively affecting surface water supplies (*Rettkowski v. Dept. of Ecology*, 1993). Even so, five more years would pass before, late in the summer of 1990, Ecology finally responded to the ranchers' complaints by issuing an order for irrigators to "cease and desist" groundwater pumping in the Sinking Creek Basin (*Rettkowski v. Dept. of Ecology*, 1993).

Rettkowski, whose well had been part of one study, and other irrigators sided against Ecology and the ranchers who called for the shutdown in a case known as *Rettkowski v. Department of Ecology*. The irrigators demanded that Ecology not issue any orders until an adjudication of the water rights was completed for the Sinking Creek Basin, arguing that Ecology did not have authority under the state constitution to order the shutdown, that the order was invalid, and that the irrigators had been denied a chance to defend their water rights in court (*Rettkowski v. Dept. of Ecology, 1993*).

In Washington state, "A general water right adjudication is a legal process conducted through the State Superior Court that determines the validity and extent of existing water rights in a given area" (Washington Dept. of Ecology, n.d.). The adjudication is treated like a regular trial in which those seeking water rights are defendants and Ecology is the plaintiff (Washington Dept. of Ecology, 2009). The adjudication determines the priority date, purpose of use, quantity of water, point of diversion, place of use, and any limitations to each water right in a given basin (Washington Dept. of Ecology, 2006). Although Ecology can instigate an adjudication, it has no authority to conduct the actual determination of water rights based on its own study. That power rests within the courts, not the agency. This process is designed to ensure that everyone involved has an opportunity to present evidence supporting their own water rights during the adjudication process.

The Supreme Court made its decision in September of 1993, siding with the irrigators in declaring that based on the constitutional rules, Ecology has no authority to determine water rights, nor can Ecology enforce rights that have not undergone a general adjudication by the Superior Court in the county where the water is located. They agreed that the purpose of adjudication is to ensure that water rights are determined in courts where each party has an opportunity to present evidence and argument in support of its own water rights.

In *Rettkowski v. Department of Ecology*, two judges dissented the majority opinion. They argued that Ecology has authority to issue permits without adjudication, but as soon as the permit is issued Ecology has no authority to regulate the water withdrawal (*Rettkowski v. Dept. of Ecology*, 1993). The dissenting judges wrote,

> if a week [after issuing a permit] it became clear that water use under the permit was impairing a senior right, Ecology could not act to protect the senior water user because that would constitute an adjudication of the water rights involved. That is an absurd result

and should be avoided. (*Rettkowski v. Dept. of Ecology*, 1993)

According to one expert who was involved with this case, the legislature should have moved in immediately and fixed the problem of Ecology's lack of authority over its own permits, but they never did. Now rather than having to take responsibility for the permits they issue Ecology can say, "We don't have the jurisdiction to take care of these problems so it's not our fault."

In addition, the dissenters wrote that the adjudication solution offered was "prohibitively expensive," writing that, "interminable litigation is what the majority has fashioned as a solution, and to no purpose. … [A] general adjudication … is now the only relief which the majority opines is available" (*Rettkowski v. Dept. of Ecology*, 1993). To this date, over 15 years after the *Rettkowski v. Department of Ecology* decision, there are about 170,000 unadjudicated water claims in the state (Washington Dept. of Ecology, 2009).

Because so many of the water resources in the state have not been adjudicated, no one really knows how much water is available, who has the senior claims, or whether water actually exists to fulfill all of the claims that are held (Washington Dept. of Ecology, 2009). These gaps in information can limit the capacity to plan for water management and cause senior water rights to go unrecognized (Washington Dept. of Ecology, 2009).

Hubbard v. State of Washington

Between 1979 and 1992, two brothers James and John Hubbard bought land, planted orchards, and applied for well permits for irrigation in the Wagonroad Coulee, a valley near the Okanogan River. While investigating the Hubbards'(Figure 13) permit applications in 1992, Ecology determined there was significant continuity between the Wagonroad Coulee Aquifer and the Okanogan River. Ecology granted permits for withdrawal of specified amounts of water from the Hubbards' wells for beneficial uses such as irrigation and frost protection under the condition that the wells would have to be shut down whenever the Okanogan River fell below its minimum instream flow (*Hubbard v. State of Washington*, 1997).

In Washington, "minimum instream flows" are essentially surface water rights for a specific amount of water that must remain in the rivers. Minimum instream flows first came about as part of the Water Resources Act of 1971, and are treated just like any other water appropriation with a priority date of their date of establishment. The minimum instream flow for the Okanogan River was established in 1976, and has priority over subsequent water rights appropriators, such as the Hubbards. If groundwater has significant hydrologic continuity with the surface water in the river, those permits are subject to the same restrictions as permits for surface water withdrawals from that resource, which in this case is a prohibition against withdrawing water during periods of low instream flow (*Hubbard v. State of Washington*, 1997).

The Hubbards appealed their conditional water permit, claiming there is no significant continuity between their aquifer and the river. They contend the Board was wrong in concluding that the Okanogan River's minimum instream flow is senior to their rights and that a significant continuity exists between the underground water source of their wells and the river (*Hubbard v. State of Washington*, 1997).

Figure 13: Washington Wildlife and Recreation Coalition, Methow Farmland, Okanogan County, WA., Retrieved 26 April 2010 from http://www.wildliferecration.org/wwrp-projects/projects/Farmland_Preservation

This case was heard by the Third Division Court of Appeals in Washington, who decided that the term "significant" applies only to the continuity between the ground and surface water, not to the effects of the withdrawals. Because the effects of pumping groundwater will eventually reach the river there is significant continuity no matter whether the "use" (in this case 0.004% of the river) is significant or not. In addition, the court held that, "Any effect on the river during the period it is below the minimum instream flow level conflicts with existing senior rights (such as the minimum flow level itself) and may be reasonably considered detrimental to the public interest" (*Hubbard v. State of Washington*, 1997). In conclusion, the court decided that the conditional permits granted by Ecology were reasonable.

Postema v. Pollution Control Hearings Board

Following the Hubbard decision, Ecology continued to deny groundwater withdrawal permit applications in watersheds where the groundwater is in hydraulic continuity with surface water where minimum instream flows are not met for a substantial part of the time or where surface water sources are closed to further surface appropriation. In 1995 and 1996 Ecology denied over half of about 600 water permit applications due to unmet minimum instream flows.

Eventually, five of the cases were consolidated and reached the Supreme Court as *Postema v. Pollution Control Hearings Board* (PCHB) (2000). The groundwater users reasoned that Ecology had no authority to deny a groundwater application if effects on the surface waters were not measurable, arguing that, “hydraulic continuity alone is an insufficient ground for denial” (*Postema v. PCHB*, 2000).

The decision of the Supreme Court including the following responses:

1)Minimum instream flows are not limited water rights that may be overridden

2)A groundwater permit may be denied even if direct and measurable impact on surface water using standard stream measuring devices has not been shown

3)An application for a permit to withdraw groundwater must be denied if “it is established factually that withdrawal will have any effect on flow or level of surface water”

4)Denial of a groundwater appropriation permit must be based on a finding of actual, not just possible, impairment of minimum surface water flows

Washington has made great progress in using its courts to clarify the application of its ground and surface water management rules and laws, but only proper adjudication can provide the complete information necessary for thorough and precise management of Washington water supplies.

One adjudication process in the Yakima Basin has been ongoing for over 30 years and has come before the state Supreme Court twice (*Rettkowski v. Dept. of Ecology*, 1993). Meanwhile, only 10% of the land area in Washington State has been adjudicated (Unger, 2007). In 2005 and 2006 bills proposing water courts as an entity that could facilitate water adjudications were raised in the state legislature, but died both years (Unger, 2007.)

In 2005, minutes from the Washington State Board for Judicial Administration indicated that the establishment of water courts was a low priority in the state legislature and that concerns had been raised about the selection and terms of water judges as presented in the bill (Cryderman, 2005).

An adjudication has still not been conducted in the Sinking Creek Basin. The irrigators may have won the argument for adjudication in 1993, but water use still goes unregulated as the adjudication is pending. Ranchers feel that their senior rights have been ignored by the authorities. One Sinking Creek rancher talked to a news reporter in 1993: “‘It’s first in time, first in right,’ he says through clinched teeth. ‘Do I get mad when I think about it? You're damn right I do’” (Wallace, 1993). On the other hand, irrigators believe that when the adjudication is conducted, “the ranchers may find they don't have as much right to the water as they think” (Wallace, 1993).

Washington: Challenges for the Future

Ecology has made modernization of water rights adjudication a legislative priority in 2009 (Washington Dept. of Ecology, 2009). Already the department has published documents outlining plans to streamline and simplify the adjudication process such as by allowing small adjudications rather than basin-wide, promoting use of conference calling and mail rather than person to person negotiations, and encouraging “courts to direct parties toward alternative dispute resolution” (Washington Dept. of Ecology, 2009).

However, other problems exist that will also need to eventually be sorted out by the courts. For example, in Washington, any well that pumps less than 5,000 gallons per day of water is exempt and does not require a permit from Ecology. According to a water expert interviewed at Ecology, “In areas where the water if fully appropriated and many of these wells go in, they are cumulatively stealing water from senior right holders. It is just a matter of time before we will have a lawsuit about this.” Water management faces many challenges, especially as Washington’s population continues to grow and climate change reduces water supplies (Unger, 2007). Washington has an estimated 0.5 million wells with about 8,000 wells being added per year (Unger, 2007).

Arizona

Arizona Overview

Arizona separately manages its ground and surface water. Surface water is subject to Arizona's appropriation doctrine, while groundwater is subject to Arizona's groundwater code as established by the Groundwater Management Code of 1980 ("the Code"). Therefore, it is crucial to determine whether the water in question qualifies as ground or surface water. Groundwater is defined as "any waters under the surface of the earth, unless the water is flowing in an underground stream with ascertainable beds and banks" (Arizona Revised Statute § 45-101(5)). Unless the groundwater to be pumped is located in an Active Management Area (AMA) or an Irrigation Non-expansion Area (INA), the water may be extracted to the extent necessary for a beneficial purpose, regardless of its effect upon surface waters. Groundwater extraction in AMAs is limited to historical uses and a very limited list of activities for which a groundwater withdrawal permit may be granted (Arizona Revised Statute § 45-452). In an INA, only groundwater pumping for new irrigation purposes is limited (Arizona Revised Statute § 45-437).

Figure 14: U.S. National Park Service. Grand Canyon National Park, AZ. Retrieved July 16, 2009, from http://www.doi.gov/photos/highresolution/Grand%20Canyon%202.jpg.

Arizona Constitutional Provisions

Article XVII §§ 1-2 of Arizona's State Constitution establishes that "riparian water rights" will not be recognized in Arizona and that all "existing rights to beneficial uses of water" shall be recognized (Arizona Constitution, Article XVII §§ 1-2). In other words, Arizona's Constitution basically sets forth that appropriation is the guiding doctrine and that beneficial uses of water are necessary for an appropriation of water. Arizona has further codified that "the waters of all sources…belong to the public" and are subject to appropriation to be limited by beneficial use (Arizona Revised Statute § 45-141)

Arizona Groundwater Management

Arizona does not conjunctively manage its surface and ground waters (Bryner and Purcell, 2003, p. 7). Surface waters are governed by Arizona's doctrine of prior appropriation, and in order to appropriate surface water in Arizona, a user must file an application for a permit with ADWR (Bryner and Purcell, 2003, p. 7). Groundwater is defined as any waters under the surface of the earth, unless the water is flowing in an underground stream with ascertainable beds and banks (Arizona Revised Statute § 45-101(5)). Until 1980, the only regulation of groundwater law was the common law doctrine of "reasonable use" (Blomquist et al., 2001, p. 653). The reasonable use doctrine limits withdrawals to what is necessary for beneficial purposes. Water cannot be simply wastes and may not be transported off the land if it interferes with the rights of adjacent landowners. In 1980, Arizona enacted the Code in order to control overdraft conditions (Arizona Revised Statute § 45-101).

The Arizona Department of Water Resources (ADWR) is responsible for regulating and administering all laws relating to surface and groundwater (Arizona Revised Statute § 45-103). The director of ADWR has "general control and supervision" of surface and groundwater as well as authority to develop programs relating to the management, conservation and utilization of both surface and groundwater basins in this state (Arizona Revised Statute § 45-105).

The Code established three levels of water management: AMAs, INAs, and general statewide provisions. There are currently five AMAs (Arizona Revised Statute § 45-411). However, the director may designate a new area if necessary to preserve groundwater for the future, to prevent land subsidence or to prevent water degradation (Arizona Revised Statute § 45-412). The AMAs are the only basins in Arizona where groundwater rights have been quantified (Blomquist et al., 2001, p. 664). No new acreage may be irrigated in an AMA (Arizona Revised Statute § 45-452). In order to extract groundwater in an AMA, a person must have a grandfathered water right or a groundwater withdrawal permit to extract groundwater from a non-exempt well. Groundwater withdrawal permits in AMAs are limited to seven categories as set forth in Arizona Revised Statute § 45-512.

Grandfathered groundwater rights in the initial AMAs are determined by the groundwater use for the five-year period prior to 1980 (Staudenmaier, 2006, p. 19). Such rights are known as grandfather rights and fall within one of three categories: Irrigation Grandfathered Rights; Type 1 Non-Irrigation Grandfathered Rights; and Type 2 Non-Irrigation Grandfathered Rights (Bryner and Purcell, 2003, p. 9). "Irrigation Grandfathered Rights" are appurtenant to the irrigated lands and may not be transferred for use on other lands (Arizona Revised Statute § 45-465). "Type 1 Non-Irrigation Grandfathered Rights" arise from retired irrigation rights (Arizona Revised Statute § 45-464). These rights are valid if approved by the director in conformance with Arizona Revised Statute § 45-469. "Type 2 Non-Irrigation Grandfathered Rights" are based upon historic non-irrigation groundwater uses and may be sold, leased or moved within the AMA freely (Staudenmaier, 2006, p. 20).

The director may designate INAs if "there is insufficient groundwater to provide a reasonable safe supply for irrigation and current rates of withdrawal" and "establishment of an AMA is not necessary (Arizona Revised Statute § 45-432)." In an INA, only land that was legally irrigated in the prior 5 years to the INA's creation may be irrigated by groundwater, effluent, diffused water or surface water (Arizona Revised Statute § 45-437).

Arizona: Conflict between Surface and Groundwater Users

In contrast to the moister mountainous states of Idaho, Washington, and Colorado, Arizona has an arid climate and few headwaters. Most of Arizona's water consumption is taken from the Colorado River (39.8%) or groundwater aquifers (43.6%) (Arizona Department of Water Resources, 2009b). Arizona does not manage its surface and groundwater conjunctively. This has allowed for some benefits, such as one of the most forward-looking groundwater management programs in the United States, as well as some problems, including lack of protection for surface water sources that may be drawn down by groundwater withdrawals.

Arizona: Outcomes and Challenges

The Overdraft Problem

In Arizona, groundwater does not fall under the Prior Appropriation Doctrine and was pumped more or less without oversight throughout much of the state's existence. (Figure 15). Arizona has been taking more water from underground supplies than it was able to recharge, a situation known as overdrafting," since the 1940s (Jacobs). As can be guessed, there are several significant problems associated with overdrafting, including increased expense of drilling as wells must go deeper to reach the lowered water table, decreased water quality because deeper water tends to have more salts and minerals dissolved into it, and cracking and settling of surface lands as the support offered by underground water is removed (Arizona Department of Water Resources, 2009b). In addition, overdrafting is not sustainable for the long term as sources of water cannot replenish.

In response to these problems, Arizona passed the Groundwater Management Code of 1980 ("the Code"), which sought to address concerns about lowering aquifer levels throughout the state by taking control of overdraft issues, allocating the available groundwater resources, and creating plans to augment diminishing groundwater resources (Arizona Department of Water Resources, 2009b). In addition to creating the Arizona Department of Water Resources (ADWR) to administer groundwater management throughout the state, the Code describes three management approaches for groundwater resources: 1) general statewide provisions, 2) more specifically controlled Irrigation Non-Expansion Areas (INAs), and 3) the most rigorous Active Management Areas (AMAs). The Code addressed the state's attitude of promoting limitless development by creating a shift toward seeking sustainable water use practices. The main goal of the Code is to achieve "safe-yield" from aquifers by 2025, meaning water withdrawn will equal the water that is put into the aquifers (Arizona Department of Water Resources, 2009b).

As an example of how safe-yield might be achieved, the most rigorous water management occurs in Arizona's five AMAs. These are centered around and named after urban areas of the state where the largest water requirements exist: Phoenix, Pinal, Prescott, Tucson, and Santa Cruz (Arizona Department of Water Resources, 2009a). Although they span only a small portion of the state's surface area, the AMAs encompass the aquifers where 70% of the state's overdraft of groundwater resources has occurred. Under the Code, the AMAs seek to protect underground water resources in several innovative ways. Each of the five AMAs in the state has a detailed system of permitting and regulation outlined in a comprehensive management plan, which is updated every five to 10 years (Harvard University Kennedy School of Government, 2009).

Figure 15: Photo by Kepner, W.G. (U.S. EPA spearheaded by the Center for Biological Diversity). Riparian (cottonwood/ Goodding willow) San Pedro River Basin in southern Arizona for over ten years Hereford, AZ. Retrieved July 16, 2009, from (Shankerhttp://www.epa.gov/esd/land-sci/photo06.htm.

New irrigation is prohibited within the AMAs (Arizona Department of Water Resources, 2009b). Developers must demonstrate that a 100-year supply of water exists for any new subdivisions, housing, or other development and must apply to the ADWR for an assured water supply certificate, which they are required to publicize to potential purchasers of the development (Arizona Department of Water Resources, 2009b). Furthermore, wells must be metered and annual water withdrawal is carefully measured and reported, with penalties for anyone who uses unauthorized water (Arizona Department of Water Resources, 2009b). In addition to these provisions for groundwater management within AMAs, the Code creates programs to recharge aquifers by injecting surface water or treated wastewater underground for storage (Arizona Department of Water Resources, 2009a).

San Pedro River

One situation in particular illustrates the complexity of the conflict between surface and groundwater use and provides an example of the weaknesses of water law in Arizona. A collection of citizens and environmental groups spearheaded by the Center for Biological Diversity has fought the Arizona Department of Water Resources to protect water in the ecologically diverse San Pedro River Basin in southern Arizona for over ten years (Shankeret al., 2004).

The San Pedro River, which lies outside of a designated INA or AMA, provides habitat for over 300 bird species, including many that migrate between the United States and Mexico and two endangered species, as well as offers recreational opportunities (Davis, 2005; Bureau of Land Management, 2009). In 1998, the San Pedro Riparian National Conservation Area (RNCA) was created by Congress and was granted a water right consisting of 11,208 acre feet of water per year in the San Pedro River (Shanker et al., 2004). According to the Bureau of Land Management, "The primary purpose [of the San Pedro RNCA] is to protect and enhance the desert riparian ecosystem, a rare remnant of what was once an extensive network of similar riparian systems throughout the American Southwest" (Bureau of Land Management, 2009).

Along the San Pedro River, water managers face a paradox. The population at a military base called Fort Huachuca and the nearby municipality of Sierra Vista continue to grow, along with the numbers of new groundwater wells pumping to meet water needs for the growing population (Silver, 2005). Before 1993, the ADWR indicated that a 100-year supply of water did not exist in the basin and forced developers to share this information with purchasers, but after 1993, when water supplies were diminishing, ADWR approved water supply assurances for developers (Shanker et al., 2004). For several days in the summer of 2005, water stopped flowing in the San Pedro River (McKinnon, 2005). State agencies suggested various explanations for the halted water flow including spread of thirsty foliage along the riverbanks, late arrival of the summer rains, and drought (McKinnon, 2005). However, a representative of the environmental groups argued:

> There is a clear connection between the draining of the groundwater for subdivisions and the viability of the base flow of the San Pedro River. The state argued in court that ADWR does not have to consider impacts on the river or surface water when it makes an adequacy evaluation -- but that is tantamount to legally closing its eyes. In reality, the only way a 100-year supply of water in the Upper San Pedro Basin could possibly exist, is through the illegal denial of federal water rights and the resulting loss of the San Pedro River. (Shanker et al., 2004).

Over the following years, water flow stopped in the San Pedro River each summer before the rainy season started (Hess, 2007). One of the main responses to this conflict has come via the Upper San Pedro Partnership (USPP). The USPP is a group of private and governmental organizations with an interest in water and water management in the area that formed in 1988. One of the tasks of the partnership is to prepare each year, in collaboration with the Secretary of the Interior, a report outlining progress toward reducing overdraft and establishing safe-yield in the watershed surrounding the San Pedro River (Kempthorne & Myers, 2008, p. 3). This Congressional mandate came about to address issues of water reduction affecting listed endangered species in the San Pedro River. Though the San Pedro watershed still does not have the special management status of an AMA or INA under Arizona water law, the area receives much of the same attention in monitoring ground and surface water sources and limiting water use, as outlined in the annual reports to Congress.

Arizona: Outcomes

By carefully measuring water use and limiting new withdrawals of water, even if it means prohibiting some development, the Code has directed the state of Arizona toward a secure water supply in the future. In 1986 Harvard University gave the state of Arizona an Innovation in American Government Award, recognizing the progressive approach of the Groundwater Management Code to address issues of pressing public concern and welfare (Harvard University Kennedy School of Government, 2009). Furthermore, the Code was recognized by the Ford Foundation with a $100,000 grant to support enactment of the Code’s provisions through creation of public awareness materials, high-school curriculum about water management, and staff training for ADWR hydrologists (Ford Foundation, 2009). The awards was emphasized that no other state had attempted to manage its water resources with such foresight and comprehensiveness (Arizona Department of Water Resources, 2009a).

However, despite the glowing accolades, inevitable problems still exist with water management in Arizona. Protection of water resources threatens to limit growth in some booming areas of the state, and ADWR has been accused of authorizing groundwater withdrawal for developers when the supply does not necessarily exist (Shanker et al., 2004). In addition, lawsuits have arisen disputing whether groundwater withdrawals affect surface water sources (Shanker et al., 2004).

Already in Arizona other rivers, including the Santa Cruz, which flows through Tucson, have dried up due to a combination of factors, which may include drought, overdrafting of water resources, and changing vegetation (Davis, 2005). Water law in Arizona does not recognize any connectivity between groundwater and surface water supplies. While some environmental and civilian groups claim groundwater withdrawals have diminished water in rivers threatening ecosystems and compromising some endangered species, developers claim drought has caused the disappearance of the water, and scientific uncertainty means proving a true cause/effect relationship between ground and surface water is difficult (Glennon, 2002).

Arizona: Challenges for the Future

To address the problem of assuring a 100-year supply of groundwater for developments when, "ADWR's 'groundwater adequacy certificate' considers only availability for human use, not ecological considerations," a new bill was passed in the Arizona state legislature in 2007 (Kempthorne & Myers, 2008, p. 67). According to the Secretary of the Interior's report to Congress:

> This bill authorizes a county or municipality to adopt by unanimous vote an ordinance requiring an adequate water supply before any subdivision may be approved. This action, in conjunction with the establishment of the Upper San Pedro Water District, requires the director of the Arizona Department of Water Resources to adopt rules for water adequacy that are consistent with the sustainability goal of the District. (Kempthorne & Myers, 2008, p. 67)

These changes mean that water is now managed more comprehensively than ever along the San Pedro River.

However, despite the progress that has been made, challenges will continue to arise surrounding water use and management in Arizona over the coming decades. Climate predictions indicate that, "Demand for groundwater in arid and semi-arid regions of the world is expected to increase over time, not only in response to population pressures but also due to climate change. For the southwestern United States and subtropical regions worldwide, the Intergovernmental Panel on Climate Change (IPCC) projects a decrease in total precipitation as well as an increase in temperatures—both of which will add more stress to riparian systems" (Saliba & Jacobs, 2008).

Summary: Discussion and Conclusions

Management Suggestions

During the interview portion of this study, experts were asked to make suggestions for improving management of ground and surface water use conflicts in their states. One interviewee summed up the responses well by recommending a list of the necessary pieces to effective management: "Good sound science. Good studies. Good technical data. Good water law. Good administration." These components were repeatedly recommended by experts from each of the states. Two other suggestions that were raised multiple times were improving storage of water supplies and promoting cooperation when rules need to be adjusted to changing circumstances.

Wyoming is quite different from many of its neighboring states in that it enjoys a small human population and many headwaters, especially in the western half of the state. While courts in Idaho and Colorado have been sorting through surface and groundwater disputes for years, the first such conflict ever to reach the courts in Wyoming is just now being addressed. Because of its unique position, Wyoming can look at the major problems and advantages of conjunctive management in neighboring states to and integrate the best parts of each to design the most effective system possible well before large-scale conflicts well up within these borders.

Good Sound Science/Studies/Technical Data

One interviewee in Idaho said, "On the technical side, more information can always be better. As we use the tools we can improve them and they can be better. Make sure the science is as good as possible. Good science helps on the administration side to answer delivery calls and helps decide where and how to improve the aquifer."

These sentiments were repeated by another interviewee who said, "The lack of hydro-geologic evidence is the greatest barrier to effective management. This is related to science. How much does pumping of a well affect a stream and where, and therefore what should be outcome of curtailment?"

All three people interviewed about Wyoming commented on the need for good technical data. "The greatest barrier to effective management in this state is not knowing how hydrologic connectivity works." Another interviewee asked, "The biggest issue is always the scientific issue. How do you tell what water starts in the ground and ends up at the surface, and how much, and how do you know where it's moving?"

The only state where experts did not express a need for additional science was Washington. "Recently Washington had a big model [of the Yakima Aquifer] done by USGS so you can figure out if you are pumping in one place when and where and how it will affect the river. People are beginning to download the model and use it. … We have a lot of groundwater/surface water studies in Washington. Science has always been a component of our process here. There is not a shortage of science."

Another interviewee, however, countered this by saying, "Until there's been a study and models developed (which is very expensive) in every area of the state, it's possible to guess wrong and over-appropriate water."

Good Water Law

Interviewees from several states felt that their rules are on the right track, but need to be refined as they play out in the courts. An expert from Idaho said, "The greatest barrier is the lack of clarity in governing legal principles. … Each court decision clarifies the legal principles a bit more."

In Colorado, one person interviewed pointed out that the water law system, "was developed in such a way that there are now competing interests for a supply that was always limited." Now the system needs to be changed, but there is great resistance to changing any existing rules because someone gets hurt by it.

Even among some states that have incorporated groundwater into the prior appropriation system, two separate water codes still exist. In Washington, interviewees called for adoption of one unified water code. "In the one major general adjudication the court joined only surface water claimants and not groundwater claimants. Surface water claims are being adjudicated and can be regulated against but not groundwater claims."

Good Administration

Because water management involves competition among many users for a supply that spans a large area, careful oversight and regulation of the resource is absolutely necessary. Administration is closely linked to water law; once the laws have been created, administrators actually distribute the limited water supplies through curtailments and water calls and implementation of other rules. One interviewee in Idaho stressed the benefits of having effective administration by saying, "We've been blessed with a good director of IDWR in Idaho. The IDWR has taken a serious, even-handed approach to the question of how to integrate conjunctive management."

Balancing administrative approaches with all the other components of water management is also important. "When people make delivery calls there [has to be an] active administration to answer it. Some people focus just on management side. Well, that's important, but it doesn't eliminate need for administration during shortages and conflicts. The goal is to minimize the need for administration by better management and storage."

Improving storage

One interviewee from Idaho recommends addressing water conflicts by finding, "more storage and looking at additional supplies[.] … Each year 36 million acre feet flow out of Idaho in the Snake River and we only have capacity to store 8 million acre feet. Other basins can store 200-400% of their flows and we can only store 25%."

In Colorado, "the aquifer along the Front Range … is getting drawn down from development, and communities have to look for other sources of water to meet their municipal water needs." Ideas to create massive storage reservoirs in the mountains or even to pipe huge amounts of water from other watersheds have been explored as a solution to this problem.

Some states have law for artificial storage of groundwater by injecting good water into aquifers. "This law allows an entity or person to artificially store water underground and recover it later. This approach is much bigger in southwest (such as in Arizona), but it is relatively new here (Washington). We see it as a strategy that could work well."

Arizona has probably done the most of any state in this investigation with underground water storage. For example, subdivisions can only be built if they have an assured water supply for 100 years. "[T]he supply of water to the subdivision cannot be groundwater. You can use water that is transported from the Colorado River in canals or, if you can't take Colorado River water directly, you can pay a replenishment district to use Colorado River water to recharge groundwater supplies and then you can pump." Arizona's goal of achieving "safe yield" in all Active Management Areas by 2025 entails accounting for both natural inflows to aquifers and injecting water.

Cooperation and collaboration

One interviewee identified "the difficulties of communication and cooperation" as the greatest barrier to effective management of ground and surface water. "You can fight forever in the courtroom. It's harder to sit down and talk and come up with a solution that allows everyone to move forward. There have been some recent settlement frameworks that are monumental successes, but they require cooperation and setting aside preconceived ideas."

An interviewee in Washington pointed out the importance of, "convincing the public about connectivity because there is so much ignorance about how groundwater works. If the state sets an instream flow and says we're going to limit surface and groundwater to protect that flow, people get all up in arms. It takes a lot of effort to educate the public, especially when there is a lack of full understanding even by ourselves of groundwater."

In Wyoming the sentiment of one expert is that there is a preference, "to have water users work it out among themselves. Work collectively. … The water users are the ones who know the most about what is going on." Effective management of such a complex and valuable resource that is increasingly in short supply will take collaboration and input from many different stakeholders.

References Cited in Part 1.

American Falls Reservoir Dist. No. 2 v. IDWR (Supreme Court of Idaho, 2007).

Arizona Department of Water Resources. (2009a). About ADWR. Retrieved Feb. 20, 2009, from Arizona Department of Water Resources: http://www.azwater.gov/dwr/Content/Find_by_Category/About_ADWR/default.htm

Arizona Department of Water Resources. (2009b). Overview of the Arizona Groundwater Management Code. Retrieved Feb. 20, 2009, from Securing Arizona's Water Future: www.adwr.state.az.us/dwr/Content/Publications/files/supplydemand.pdf

Associated Press. (2001, Aug). Junior water rights users could lose access next year. Retrieved Jan 22, 2009, from Idaho Statesman: http://elibrary.bigchalk.com/libweb/elib/do/search

Berg, S. (2008, Dec 10). Water meeting tonight: Officials looking to develop long-term strategy. Retrieved Jan 23, 2009, from Lexis Nexis: http://www.lexisnexis.com/us/lnacademic/

Blomquist, W., et al. (2001). Institutions and Conjunctive Water Management Among Three Western States. Natural Resources Journal, 41, 653.

Bower v. Big Horn Canal, 307 P.2d 593, 602 (Wyoming 1957).

Bryner, G. and E. Purcell. (2003, Sep.) Groundwater Law Sourcebook of the Western United States.

Bureau of Land Management. (2001, Aug. 15). Arizona Water Rights Fact Sheet. Retrieved Feb. 25, 2009, from http://www.blm.gov/nstc/WaterLaws/arizona.html

Bureau of Land Management. (2009, Feb. 23). San Pedro Riparian NCA. Retrieved Mar. 2, 2009, from Bureau of Land Management, Arizona: http://www.blm.gov/az/st/en/prog/blm_special_areas/ncarea/sprnca.html

California Department of Water Resources. (2004, Aug.). Conjunctive Water Management Program, Update 2004. Retrieved May 12, 2009, from www.groundwater.water.ca.gov/cwm/docs/CWM_Annual_Report_2004.

Christensen, M. (2007, Oct 24). The rush for recharge: Officials in a race against winter to replenish aquifer. Retrieved Jan 29, 2009, from Times-News: http://www.magicvalley.com/articles/2007/10/24/news/top_story/123241.txt

City of Boulder. (2006, Nov 28). Issue Points on South Platte River Wells. Retrieved Jan 29, 2009, from City Boulder, Colorado: South Platte River Wells: http://www.bouldercolorado.gov/index.php?option=com_content&task=view&id=6166&Itemid=1189

City of Boulder. (2008, Aug 21). City of Boulder, Colorado: South Platte River Wells. Retrieved Jan 26, 2009, from http://www.bouldercolorado.gov/index.php?option=com_content&task=view&id=6166&Itemid=1189#STATUS

Colorado Division of Water Resources. (2007, June). Well Regulation in the South Platte River Basin of Colorado. Retrieved Jan 26, 2009, from Colorado Dept. of Agriculture: South Platte Task Force: http://www.colorado.gov/cs/Satellite/Agriculture-Main/CDAG/1184748122275

Colorado Division of Water Resources. (2008, Jun 10). Information Concerning South Platte Alluvial Wells that Have Limited or No Pumping Allowed in 2008. Retrieved Jan 27, 2009, from http://water.state.co.us/pubs/pdf/spwellsummary.pdf

Colorado Division of Water Resources. (n.d.). History of Water Rights in Colorado. Retrieved Jan 29, 2009, from The Office of the State Engineer: http://water.state.co.us/org/history.asp

Colorado Judicial Dept.. (n.d.). Water Courts. Retrieved Jan 26, 2009, from Colorado Courts: http://www.courts.state.co.us/Courts/Water/Index.cfm

Cryderman, J. (2005, June 17). Board for Judicial Administration meeting minutes. Retrieved Feb. 12, 2009, from Washington Courts: http://www.courts.wa.gov/programs_orgs/pos_bja/?fa=pos_bja.meetingInfo&theFile=20050617

Davis, G., Nichols, M., & Spear, M. (2003, Oct.). California's Groundwater - Bulletin 118, Update 2003. Retrieved May 12, 2009, from http://www.groundwater.water.ca.gov/bulletin118/update2003/index.cfm

Davis, T. (2005, Jul. 13). San Pedro River is running dry. Arizona Daily Star.

Dunlop, M. (2005, Nov 10). Idaho water law in question. Retrieved Jan 22, 2009, from Times-News (Twin Falls, Idaho).

Dunlop, M. (2006, Jul 14). Pumpers win temporary reprieve. Retrieved Jan 22, 2009, from Ag Weekly: http://www.agweekly.com/articles/2006/07/14/news/ag_news/news05.txt

Environment and Energy Publishing, LLC. (2006, Dec 11). Water: Idaho Supreme Court hears rights case. Retrieved Jan 24, 2009, from Lexis Nexis: http://www.lexisnexis.com/us/lnacademic/

Environment and Energy Publishing, LLC. (2007, Mar 7). Water: Idaho Supreme Court rules against prior allocation. Retrieved Jan 24, 2009, from Lexis Nexis: http://www.lexisnexis.com/us/lnacademic/

Environmental Hearings Office. (2008). Pollution Control Hearings Board. Retrieved Feb. 12, 2009, from http://www.eho.wa.gov/Boards_PCHB.aspx

Foley-Gannon, E. (2000). Institutional Arrangements for Conjunctive Water Management in California and Analysis of Legal Reform Alternatives. Hastings West-Northwest Journal of Environmental Law and Policy, 6(2 & 3), 273.

Ford Foundation. (2009). Groundwater Management Code, State of Arizona. Retrieved Mar. 2, 2009, from Innovations in State and Local Government: http://www.fordfound.org/archives/item/0284/text/6

Fundingsland v. Colorado Ground Water Commission (Supreme Court of Colorado, 1970).

Glennon, R. (2002, Oct. 1). The perils of groundwater pumping. Issues in Science and Technology , p. 73.

Harvard University Kennedy School of Government. (2009). Groundwater Management Code, 1986 Winner. Retrieved Mar. 2, 2009, from Government Innovators Network: http://www.innovations.harvard.edu/awards.html?id=3484

Hess, B. (2007, Jul. 7). Gauging the river. The Sierra Vista Herald .

Howe, C. W. (2008, May 12). Is There a Conflict Between Western Water Law and Efficient Use of Water Resources? (I. W. Parry, Ed.) Retrieved Jan 28, 2009, from Resources for the Future Weekly Policy Commentary: http://www.rff.org/Publications/WPC/Pages/08_05_12_Water_Resources_Howe.aspx

Hubbard v. State of Washington, No. 15227-8-III (Court of Appeals of Washington, Division 3, Panel Three May 1, 1997).

Hunziker v. Knowlton, 322 P.2d 141, 144 (Wyoming 1958).

Idaho Dept. of Water Resources. (2009, Jan). Comprehensive Aquifer Management Planning. Retrieved Jan 23, 2009, from http://www.idwr.idaho.gov/waterboard/Planning/CAMP/CAMP.htm

Idaho Water Resource Board. (2005). Fiscal Year 2005 Annual Report. Retrieved Jan 24, 2009, from Idaho Dept. of Water Resources: http://www.idwr.idaho.gov/waterboard/Financial%20program/Documents/annual_report/FY05AnnualReport.pdf

Jacobs, J., Tyrell, P., & Brosz, D. (2003). Wyoming water law: A summary (B). Laramie: University Of Wyoming, Agricultural Experiment Station.

Jacobs, K. (n.d.). Groundwater Management Issues and Innovations in Arizona, U.S.A. Retrieved Feb. 20, 2009, from Centro de Investigación y Technología Agroalimentaria de Aragón: admin.cita-aragon.es/pub/documentos/documentos_JACOBS_2-4_26d10f50.pdf

Kempthorne, D., & Myers, M. (2008). Water Management of the Regional Aquifer in the Sierra Vista Watershed, Arizona-2008 Report to Congress. U.S. Department of the Interior, Upper San Pedro Partnership. Reston, Virginia: U.S. Geological Survey.

Kray, Jeff. (1996). Idaho Supreme Court Decision Addresses “Prior Appropriation” Water Rights. Water Resources Update.

McKinnon, S. (2005, Jul. 15). Arizona river runs dry. The Arizona Republic .

McLaughlin, B. (2008). IDWR Issues Letters to Water Rights Holders Warning of Potential Water Curtailments Next Spring. Boise: Idaho Dept. of Water Resources.

Musser v. Higginson, 871 P.2d 809 (Supreme Court of Idaho Feb. 28, 1994).

Otter, C., & Tuthill, D. R. (2008). Notice of Potential Curtailment of Ground Water Rights in the Eastern Snake Plain Aquifer. Boise: Idaho Dept. of Water Resources.

Pence, J. (2005, Nov 18). Judge's ruling adds intrigue to water fight. Retrieved Jan 22, 2009, from Ag Weekly: http://www.agweekly.com/articles/2005/11/18/news/ag_news/news02.txt

Poppino, N. (2008, Jul 29). Joining the party: State, groundwater group spread word for pumpers to join mitigation plan. Retrieved Jan 23, 2009, from Times-News, Twin Falls: http://elibrary.bigchalk.com/

Postema v. Pollution Control Hearings Board, No. 67549-0 (Washington State Supreme Court Oct. 19, 2000).

Raines, R. T. (1996, Winter). Following the Law in Idaho: Legal and Institutional Impediments to Conjunctive Water Management. Water Resources Update.

Rettkowski v. Dept. of Ecology, 59086-9 (Washington State Supreme Court Sep. 9, 1993).

Saliba, G., & Jacobs, K. L. (2008, Nov.-Dec.). Saving the San Pedro River: Science, Collaboration, and Water Sustainability in Arizona. Science and Policy for Sustainable Development .

Shanker, H. M., Silver, R., & Burchfield, S. (2004, Jun. 8). Arizona Defends Its Right to Destroy the Last Free Flowing River in the Desert Southwest for Developers' Benefit. Retrieved Mar. 2, 2009, from Business Wire: http://elibrary.bigchalk.com/libweb/elib/do/search

Silver, R. (2005, Jun. 1). Fort Huachuca violations of San Pedro compact challenged. Retrieved Mar. 2, 2009, from Center for Biological Diversity: http://www.biologicaldiversity.org/news/press_releases/sanpedro6-1-05.html

Simpson, H. (2006, Sep 6). History of Well Regulation: South Platte River Basin. Retrieved Jan 27, 2009, from Colorado Division of Water Resources: http://water.state.co.us/pubs/presentations/hsimpson_history_090606.pdf

Snyder, C. (2006a, Nov 24). Sides prepare for day in court. Retrieved Jan 22, 2009, from Ag Weekly: http://www.agweekly.com/articles/2006/11/24/news/ag_news/news02.txt

Snyder, C. (2006b, Feb 17). Water cases proceeding. Retrieved Jan 22, 2009, from Ad Weekly: http://www.agweekly.com/articles/2006/02/17/news/ag_news/news03.txt

Staudenmaier, L. W. (2006). Arizona Groundwater Law. The Water Report, 33, 19.

Times-News editorial board. (2007, Mar 13). Watered-down justice prevails in high court. Retrieved Jan 22, 2009, from Ag Weekly: http://www.agweekly.com/articles/2007/03/13/news/opinion/opin85.txt

Unger, K. (2007, Oct. 2). Washington State Climate Change Adaptation Efforts in the Water Sector. Retrieved Feb. 12, 2009, from Climate Impacts Group: cses.washington.edu/cig/outreach/workshopfiles/olympia07/unger.ppt

U.S. Water News Online. (2004, Oct). Western drought continues to hit hard. Retrieved Jan 22, 2009, from U.S. Water News Online: http://www.uswaternews.com/archives/arcsupply/4westdrou10.html

U.S. Water News Online. (2005a, Feb). Idaho hydrologists say the water outlook deteriorating. Retrieved Jan 22, 2009, from U.S. Water News Online: http://www.uswaternews.com/archives/arcsupply/5idahhydr2.html

U.S. Water News Online. (2005b, Apr). West's water troubles getting worse, officials say. Retrieved Jan 22, 2009, from U.S. Water News: http://www.uswaternews.com/archives/arcsupply/5westwate4.html

U.S. Water News Online. (2007a, May). Another round of shutdown warnings to E. Idaho groundwater users. Retrieved Jan 21, 2009, from U.S. Water News Online: http://www.uswaternews.com/archives/arcrights/7anotroun5.html

U.S. Water News Online. (2007b, May). Idaho threatens to throttle Magic Valley groundwater users. Retrieved Jan 21, 2009, from U.S. Water News Online: http://www.uswaternews.com/archives/arcsupply/7idahthre5.html

U.S. Water News Online. (2007c, Oct). Idaho water director sending early warning about water curtailment next summer. Retrieved Jan 21, 2009, from U.S. Water News Online: http://www.uswaternews.com/archives/arcsupply/7idahwate10.html

Wallace, J. (1993, Nov. 25). Ranchers and irrigators at the heart of longtime controversy. Retrieved Feb. 13, 2009, from Seattle Post Intelligencer: http://seattlepi.nwsource.com/archives/1993/9311250091.asp

Washington Dept. of Ecology. (n.d.). Washington State Water Law: A Primer. Retrieved Feb. 9, 2009, from Washington Dept. of Ecology: http://www.ecy.wa.gov/pubs/98152/

Washington Dept. of Ecology. (2006, April). Washington State Water Right Adjudication Process. Retrieved Feb 9, 2009, from Washington Dept. of Ecology: http://www.ecy.wa.gov/pubs/98151.pdf

Washington Dept. of Ecology. (2009, Jan.). Focus on Water Rights Adjudication. Retrieved Feb. 10, 2009, from Washington Dept. of Ecology: http://www.ecy.wa.gov/pubs/0811048.pdf

Welch, C. (2001, March 11). State awash in wrangling over water rights. Retrieved Feb. 5, 2009, from

The Seattle Times: http://community.seattletimes.nwsource.com/archive/?date=20010311&slug=water11m.

Wildrick, L. (1990, Oct.). Decreasing Streamflow and Possible Ground Water Depletion in the Sinking Creek Watershed, Lincoln County, Washington. Retrieved Feb. 9, 2009, from Washington Deparment of Ecology: http://www.ecy.wa.gov/pubs/oftr8206.pdf.

Wolfe, D. (2007, Jun 29). Well Regulation in the South Platte River Basin. Retrieved Jan 29, 2009, from Colorado Division of Water Resources: http://www.colorado.gov/cs/Satellite?c=Page&cid=1184748122275&pagename=Agriculture-Main%2FCDAGLayout.

Wolfe, L., & Hager, J. (1989). Wyoming's Groundwater Laws: Quantity and Quality Regulation. Land and Water Law Review, 24(40), 50.

See also:

Idaho
Idaho Constitution – Article XV, Water Rights
Idaho Administrative Procedures Act – Idaho Statutes, Title 67, Chapter 52

Washington
Washington Constitution – Article XXI, Water and Water Rights
Revised Code of Washington
Washington Administrative Code

Colorado
Colorado Constitution – Article XVI
Colorado Revised Statutes
Colorado Code of Regulations

Wyoming
Wyoming Constitution – Article VIII
Wyoming Statutes
Rivett v. Wyoming State Engineer (not yet decided, all documents retrieved from Wyoming 7th District Court, March 2009)

Arizona
Arizona Constitution – Article XVII
Arizona Revised Statutes – Title 45

2. Development of a Modeling Framework to test Conjunctive Management Strategies: Demonstration on the Bates Creek, Wyoming, Alluvial Aquifer

Fred L. Ogden, Ph.D., P.E., P.H., Professor, Department of Civil & Architectural Engineering, University of Wyoming, Laramie, WY 82071

Kristin Flynt, Ph.D. student, Department of Civil & Architectural Engineering, University of Wyoming, Laramie, WY 82071

David P. Ahlfeld, Ph.D., P.E., Professor, Department of Civil and Environmental Engineering University of Massachusetts, Amherst, MA 01003

ABSTRACT

A contemporary modeling framework based on the USGS *MODFLOW* and *GWM* programs is presented as a methodology for developing a conjunctive management strategy within the prior-appropriations water rights doctrine. An extensive review of the literature establishes the utility of the approach, and demonstrates the breadth and depth of work that has been performed on the conjunctive management problem. The modeling framework for conjunctive management is demonstrated.

Introduction

To address anticipated future conflicts between senior surface water rights and junior ground water rights, it is necessary to develop of a functional model to identify optimal conjunctive use strategies. This project combined a legal analysis with hydrologic modeling in order to assess the viability of a number of conjunctive use water management models for alluvial aquifer systems.

Four basic legal doctrines govern groundwater development: (1) the common law "rule of capture," which allows unlimited withdrawal of water below owner's land; (2) the American rule, more common in the Eastern states, which allows "reasonable use" reasonable and beneficial purposes; (3) correlative rights, in which landowners have right to proportionate share of water; and (4) the prior appropriation doctrine, which allows those who first put water to beneficial use to continue to do so (Bryner and Prucell, 2003).

Wyoming, like most states in the West, has a permit-based prior appropriation system. Wyoming law anticipates the potential for interconnectedness of surface and groundwater supplies and provides that, in such cases, surface and groundwater rights are to be correlated into a single schedule of priorities. (Wyo Rev. Statute § 41-3-916). Ground and surface supplies are not presumed connected unless proven otherwise (Tellman, 2003). In actual application, however, conjunctive management of surface and groundwater supplies in prior appropriation systems can be problematic. In Idaho, for example, conjunctive management rules for the Snake River basin were recently struck down for failing to conform to constitutionally mandated components of the prior appropriation doctrine.

Management tools developed in other states that address conjunctive water management were surveyed. The assessment of management options include a “no management” option in which prior appropriation allocations of groundwater continue without regard to potential impacts on other water rights within the hydrologic system. “Safe yield” strategies were given particular attention, including tools for addressing the increasing need to make predictive assessments of allowable use of junior rights based on surface water availability and demands by senior rights.

Effective conjunctive management of ground and surface water resources is essential where wells pump from valley-bottom alluvial aquifers that are in contact with surface waters. Pumping from alluvial aquifers can lower the local water table in alluvial aquifers near streams below the water level in the stream. This results in a vertical head gradient into the stream bed, and causes the stream to lose water to the alluvium, a process that is called “induced infiltration”.

Alluvial wells are not in intimate contact with the surface water. There are limits to water transfers from the surface water body or stream to the alluvium, attributed to streambed hydraulic conductivity, porosity and hydraulic conductivity of the alluvium, pumping rates, intercepted recharge, the distance from the well(s) to the stream (Ahlfeld 2004, Nadim et al. 2006), and fluvial geomorphology (Woessner, 2000).

Establishing a mechanism for effective conjunctive management requires 1) identification of potential operational management strategies; 2) development of a scientifically-sound means of justifying the action; 3) accurate description of all surface water and groundwater rights; and 4) identifying the magnitude of all relevant physical characteristics (model parameters) that describe the conjunctive system.

This report describes data needs, reports on similar past and ongoing efforts elsewhere in the Western U.S., and applies standard USGS methodologies on the Bates Creek irrigation district near Casper, Wyoming, as a demonstration of the approach using literature parameter values and assumed surface discharges and pumping rates. The purpose of this demonstration is not to provide a final management plan, rather it is to show how a management plan might be developed.

Review of Literature

The problem of management of conjoined surface and ground waters is vexing. Much work has been done on the problem, yet a single best methodology has not been developed to date. Since the 1970's numerical modeling approaches have been the predominant means of trying to determine the effect of groundwater pumping on stream flows. Today, the majority of studies involve the U.S. Geological Survey three-dimensional, finite difference MODFLOW (Harbaugh and others, 2000) groundwater simulator with a variety of add-on packages for simulating surface water flow and constraint-based optimization aimed at minimizing negative impacts.

Wilson and Anderson (2006) performed a literature review that identified a number of relevant published papers, which is presented in Table 1 in an updated form to inform the reader of the scope of work that has been published on modeling to address the subject of this report.

Table 1. Recent papers related to conjunctive ground- and surface-water management. Note: DSS stands for "Decision Support System". (Updated from Wilson and Anderson, 2006)

Region	Author(s),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
	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, 2006	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
	NRC, 2000	Groundwater Management at Regional and National Scales
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., 1990	Optimal management of conjoined waters
California	Andrews et al., 1992	Simulating surface water distribution; KCOM
	Bergfeld, L. G.	Investigative study of conjunctive use opportunities
	Dvorak, 2000	Operating rule effects on yield
	Fleckenstein et al. 2006	MODFLOW low-flow management
	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
Connecticut	Nadim et al. 2007	MODFLOW instream flow, fisheries maintenance
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
Nebraska	Cannia et al., 2002	Hydrostratigraphic units for COHYST
	Carney et al., 2002	Stream depletion and COHYST
	Henszey et al., 2002	Water levels versus grass response curves
	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
	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
Spain	Pulido-Velazquez, et al., 2006	Economic optimization of conjunctive use
Texas	Watkins and McKinney, 1999	Alternative screening model
Washington	Scott et al., 2004	Forecasting climate variability
Wyoming	Glover, 1983	Conjunctive management modeling

Similar Efforts Elsewhere

Colorado

In 2003, the Colorado legislature recognized the importance of planning for long-term water needs. In that year, the legislature authorized the Colorado Water Conservation Board (CWCB) to initiate a Statewide Water Supply Initiative (SWSI), with the overarching objective of maintaining an adequate water supply for the State. As part of this effort, development started on River Decision Support Systems (RDSS), which were planned for each major drainage basin. The resulting product is called the Colorado Decision Support Systems (CDSSs). The major goals of the CDSSs are to:

- Develop accurate, user-friendly databases that are helpful in the administration and allocation of waters of the State of Colorado,
- Provide data, tools and models to evaluate alternative water administration strategies, which can maximize utilization of available resources in all types of hydrologic conditions,
- Be a functional system that can be used by decision makers and other and be maintained and upgraded by the State, and,

- Promote information sharing among government agencies and water users.

This effort has been funded at approximately $500,000 per year since 2003. Support for the RDSS by the Colorado legislature in FY08-09 was $535,000. In FY 09-10 funding for the RDSS was $453,000 to the Colorado Water Conservation Board plus another $205,400 to the Water Resources Division, which funds 6 FTE staff. The CDSS effort is most advanced on the South Platte river, where the effort is aimed at setting up a single-layer *MODFLOW* model of the alluvial aquifer. The model active area is approximately 2500 square miles, and the model uses a 1,000 ft. grid size, and monthly stress periods. The CDSS has an external peer-review panel which meets regularly to evaluate progress, engage the advice of experts, and plan future developments. As of the last report in 2009, the CDSS is being calibrated in the South Platte alluvial aquifer.

Nebraska

The States of Wyoming, Colorado, Nebraska, and the U.S. Fish and Wildlife Service and Bureau of Reclamation, entered into an agreement which is called the Platte River Cooperative Agreement in 1997 to address minimum in-stream flows to maintain aquatic habitat for endangered species in the central Platte River in Nebraska. Part of this agreement requires no new depletions of Platte River flows or flows to tributary streams. As part of this cooperative agreement, a Cooperative Hydrology Study (COHYST) is underway, which aims to create scientifically supportable data sets and modeling capabilities to address the problem. To date, well over $1 million has been spent on this study. In February, 2010, COHYST received a grant of $500,000 to combine the Conjunctive Management Study and COHYST data bases.

MODFLOW

The USGS groundwater simulation code MODFLOW (Harbaugh et al., 2000, McDonald and Harbaugh, 1988) is widely used to analyze groundwater flows in the United States and abroad. *MODFLOW* can describe the three-dimensional variation of aquifer properties using a finite-difference discretization. The formulation of *MODFLOW* is modular allowing the addition of process modules as the situation requires. These add-on process modules include simulation capabilities for lakes, streams, and land-surface recharge, among others. The stream packages *STR*, *SFR*, and *SFR2* (Prudic, 1989; Prudic et al., 2004; Niswonger and Prudic, 2005) were developed to improve the ability of *MODFLOW* to simulate conjoined surface and ground waters. The most recent stream routing module *SFR2* includes unsaturated flow beneath streams that are above the water table. All three of these stream routing modules treat surface flows as steady. Exchanges of water from the stream to the aquifer is assumed to be controlled by a stream bed layer of known thickness and hydraulic conductivity.

The USGS had developed more sophisticated streamflow modeling approaches that can be used to simulate unsteady flows. These include *DAFLOW* (Jobson and Harbaugh, 1999) and *MODBRANCH* (Schaffrenek, 1987). The *DAFLOW* scheme solves the 1-D diffusive-wave form of the de St. Venant equation of motion, while *MODBRANCH* uses a 4-point implicit solution of the full-dynamic form of the de St. Venant equations. Both of these schemes use an iterative approach to calculate the coupled changes in groundwater head and surface water depth over a time step.

The *DAFLOW* scheme was developed to simulate unsteady flows in low-order streams, and

Jobson and Harbaugh (1999) report that the accuracy of the method is higher in steeper streams. The full dynamic-wave representation used in *MODBRANCH* in theory should be more accurate in all streams, however the four-point implicit solution has known deficiencies in situations where flow is transcritical as can often occur in steep reaches or at significant channel constrictions such as bridge openings (Meselhe and Holly, 1997).

Given that high-temporal resolution surface flow data do not exist in Bates, Corral, and Stinking creeks, the unsteady flow simulation capabilities offered by the *DAFLOW* and *MODBRANCH* models are not needed. We opted therefore to use the SFR2 stream flow routing package in MODFLOW simulations of the Bates creek study area because it has the level of sophistication required to simulate the salient surface-water flow features required in this study, particularly surface water diversions, which are not part of the *STR* and *SFR* packages. The SFR2 package also includes unsaturated zone flow beneath streams (Niswonger et al, 2006). The use of the SFR2 package, however, required use of the 2005 version of *MODFLOW* (Harbaugh, 2005) which is a difference from our original proposal, which called for the use of the 2000 version of *MODFLOW*.

***MODFLOW* Interface Selection**

This project aims to recommend a numerical modeling framework for use by the Wyoming State Engineer's office. As such, creation of data sets for a model such as MODFLOW requires the use of an interface to process geo-spatial data and produce model inputs. There are a number of options for this task, we considered two different options, which are discussed below.

The first *MODFLOW* interface considered is called Argus ONE (Argus ONE Ltd., 2010). The actual *MODFLOW* graphical user interface (GUI) is available at no cost from the USGS, but before it can be used, the user must purchase the Argus ONE GIS and Grid modules, which cost $1000 at the time of writing. Furthermore, Argus ONE is a GIS system with its' own data structures and learning requirements. Given the prevalence and widespread acceptance of the *ARC/INFO* Geographic Information System, the Argus ONE requirement that users learn a new GIS software package just to run *MODFLOW* was seen as a major drawback.

The Groundwater Modeling System (*GMS*) interface for *MODFLOW* (Aquaveo LLC, 2010) is a full *MODFLOW* GUI that also serves as an intermediary between *ARC/INFO* and *MODFLOW*. The *GMS* software is more expensive than the Argus ONE GIS package, with a cost of $4,450 at the time this report was written for the standard *MODFLOW* package which includes *MODPATH* particle tracking, and the (Parameter ESTimation (*PEST)* automatic model calibration tool. Given that the *GMS* serves as an intermediary package that allows *ARC/INFO* geospatial data to be used directly in *MODFLOW* setup, this capability justifies the additional cost above the cost of the Argus ONE GIS software.

The *GMS* software supports its' own customized version of *MODFLOW* that was derived from *MODFLOW* 2000. The primary customization in the GMS version of *MODFLOW* is the use of the HDF binary data storage standard, which is not used by the USGS version. The HDF data storage standard is widely used but not by the USGS. GMS can be used to create input data sets for *MODFLOW* 2005, as it has the option of writing ASCII input files that *MODFLOW* 2005 will read. Only minor text editing is required by the user before running the stock USGS *MODFLOW* 2005 code with input data written by the GMS software package.

MODFLOW Stability Issues

During a MODFLOW simulation, it is not unusual for one or more model grid cells to go dry, which means the water table is drained to the aquifer bottom. To continue the simulation, the MODFLOW code will remove a cell that becomes dry from the computational domain. MODFLOW does allow dry cells to re-wet, but the solution can become unstable. A number of different efforts to improve stability of MODFLOW during cell-rewetting have been developed (Doherty, 2001; Painter et al., 2008), but to date these techniques have not been incorporated in the main USGS code.

Another factor that can cause dry cells and affect the stability of a *MODFLOW* simulation occurs if a well is pumped at a rate that is higher than the aquifer can supply water to that well. There may be wells in the study area that can actually pump water at a rate faster than the aquifer can fill the cone of depression, and the cone of depression will reach the screen or pump elevation. In the model this creates a dry cell, and if this occurs, the user will have to break the simulation into smaller stress periods and turn the well off in the model before this condition occurs.

Ground Water Management (GWM) Optimization Code

Since the 1960s, numerical ground-water flow models have become increasingly important tools for the analysis of ground-water systems. More recently, ground-water flow models have been combined with optimization techniques to determine water-resource management strategies that best meet a particular set of management objectives and constraints.

Optimization techniques are a set of mathematical programs that seek to find the optimal (or best) allocation of resources to competing uses. In the context of ground-water management, the resources are typically the ground- and surface-water resources of a basin and (or) the financial resources of the communities that depend on the water. The management objectives and constraints are stated (or formulated) mathematically in an optimization (management) model. Combined ground-water flow and optimization models have been applied to various ground-water management problems, including the control of water-level declines and land subsidence that could result from ground-water withdrawals, conjunctive management of ground-water and surface-water systems, capture and containment of contaminant plumes, and seawater intrusion. Detailed guides to the underlying theory and application of management models can be found in textbooks by Willis and Yeh (1987), Gorelick and others (1993), and Ahlfeld and Mulligan (2000), and to literature reviews by Gorelick (1983), Yeh (1992), Ahlfeld and Heidari (1994), and Wagner (1995).

GWM (Ahlfeld et al., 2005 and 2009) is a Ground-Water Management process module for the U.S. Geological Survey modular three-dimensional ground-water model, *MODFLOW*-2000 (Harbaugh and others, 2000) and *MODFLOW*-2005 (Harbaugh, 2005). GWM uses a response-matrix approach to solve several types of linear, nonlinear, and mixed-binary linear ground-water management formulations. Each management formulation consists of a set of decision variables, an objective function, and a set of constraints.

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. Flow-rate decision variables can represent wells that extend over one or more model cells and be active during one or more model stress periods; external variables also can be active during one or more stress periods.

A single objective function is supported by *GWM*, which can be specified to either minimize or maximize the weighted sum of the three types of 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.

The Response Matrix Solution (RMS) Package of GWM uses the Ground-Water Flow Process of MODFLOW to calculate the change in head or streamflow at each constraint location that results from a perturbation of a flow-rate variable; these changes are used to calculate the response coefficients. For linear management formulations, the resulting matrix of response coefficients is then combined with other components of the linear management formulation to form a complete linear formulation; the formulation is then solved by use of the simplex algorithm, which is incorporated into the RMS Package. Nonlinear formulations arise for simulated conditions that include water-table (unconfined) aquifers or head-dependent boundary conditions (such as streams, drains, or evapotranspiration from the water table). Nonlinear formulations are solved by sequential linear programming; that is, repeated linearization of the nonlinear features of the management problem. In this approach, response coefficients are recalculated for each iteration of the solution process. Mixed-binary linear (or mildly nonlinear) formulations are solved by use of the branch and bound algorithm, which is also incorporated into the RMS Package.

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 stream flow and stream flow-depletion constraints. Two types of streamflow constraints are allowed—constraints on the upper and lower bounds on streamflow and constraints on the upper and lower bounds on streamflow depletion.

GWM allows for the simultaneous use of both managed and unmanaged wells at model cells. For example, the user might specify an unmanaged withdrawal rate (that is, a background stress) of 1.0 ft3/s at a particular cell with the WEL Package; the user also could define a managed withdrawal at the same cell by use of a flow-rate decision variable in *GWM*. The total withdrawal rate at the cell at the end of the *GWM* run would then equal the sum of the unmanaged withdrawal rate (1.0 ft3/s) and the managed withdrawal rate determined by *GWM* for the decision variable.

Output from *GWM* includes response coefficients, which represent the partial derivative of the state variable of interest (e.g. stream flow at a point) with respect to a particular stress or well pumping rate. Response coefficients are approximated using a first-order, finite-difference perturbation method. The precision of the response coefficients is an indication of their ability to reflect the actual response of the calculated system state to changes in stress. Values of head are iteratively generated until the maximum calculated change in head at any model cell is less than a specified convergence criterion between iterations. The precision of the resulting heads can be estimated to be of the same magnitude as the convergence criterion. As a result, the precision of the response coefficients depends upon the convergence criterion used by the flow process.

One significant benefit of using the *GWM* package is that response coefficients are calculate for each stress period. This information can be used to track changes in the effect of different stresses on different constraints (e.g. well pumping on stream flow) over time. Temporal changes in stress coefficients indicate lags in time. These can be interpreted as system "memory" as well. GWM results can indicate, for instance, that a well far from the stream may have a more significant effect on stream flow some time after the start of the irrigation season compared to a well that is nearer the stream.

<u>Data Needs</u>

The following data are needed to simulate the hydrogeology of the study area using *MODFLOW*:

- Bedrock surface elevations
- Land surface elevations
- Stream locations
- Lateral boundary conditions (constant head, constant flux, no-flow)
- Lower boundary conditions (flux to/from bedrock aquifer)
- Stream bed impeding layer thickness
- Stream bed impeding layer saturated hydraulic conductivity

The following data are required to develop MODFLOW stress period input data:

- Irrigation-based recharge quantities
- Irrigation Recharge areas
- Canal seepage
- Area-wide recharge from rainfall and snow melt
- Actual irrigation pumping rates and schedules
- Actual residential pumping rates
- Evapotranspiration from irrigated fields
- Evaporation from streams and bare soils
- Measured streamflow diversions and schedules
- Stream flow hydrographs at model boundaries

Calibration requires spatially-varied aquifer head data. Actual data requirements depend on the particular situation, seasonality, unsteady stresses, meteorological forcing, etc. An imperative need is that the data collection be continuous and period span sufficient time to capture seasonality and the effects of climate variability. This requires data collection over a several year period, at a minimum.

<u>Bates Creek Study Site</u>

The problem of conjunctive management in Wyoming is unique. Compared to the large river-valley irrigation projects along the North Platte and Platte Rivers in Nebraska, and the South Platte and

Arkansas Rivers in Colorado, irrigation areas in Wyoming where conjunctive management issues have arisen tend to be along smaller rivers and creeks. This project did not contain a field data collection component. Therefore, we relied upon data collected by others from a Wyoming irrigation district.

One such irrigation district in Wyoming is along Bates Creek before it joins the North Platte River. We obtained data on permitted wells and surface water diversions in the Bates Creek study area from the Wyoming State Engineer's office, and from the study by Glover (1983). The study area is located about 20 miles southwest of Casper, Wyoming. Bates Creek is a tributary to the North Platte River. Two significant drainages join Bates Creek at the upper end of the study area, Stinking Creek and Corrall Creek. The study area is shown in Figure 16.

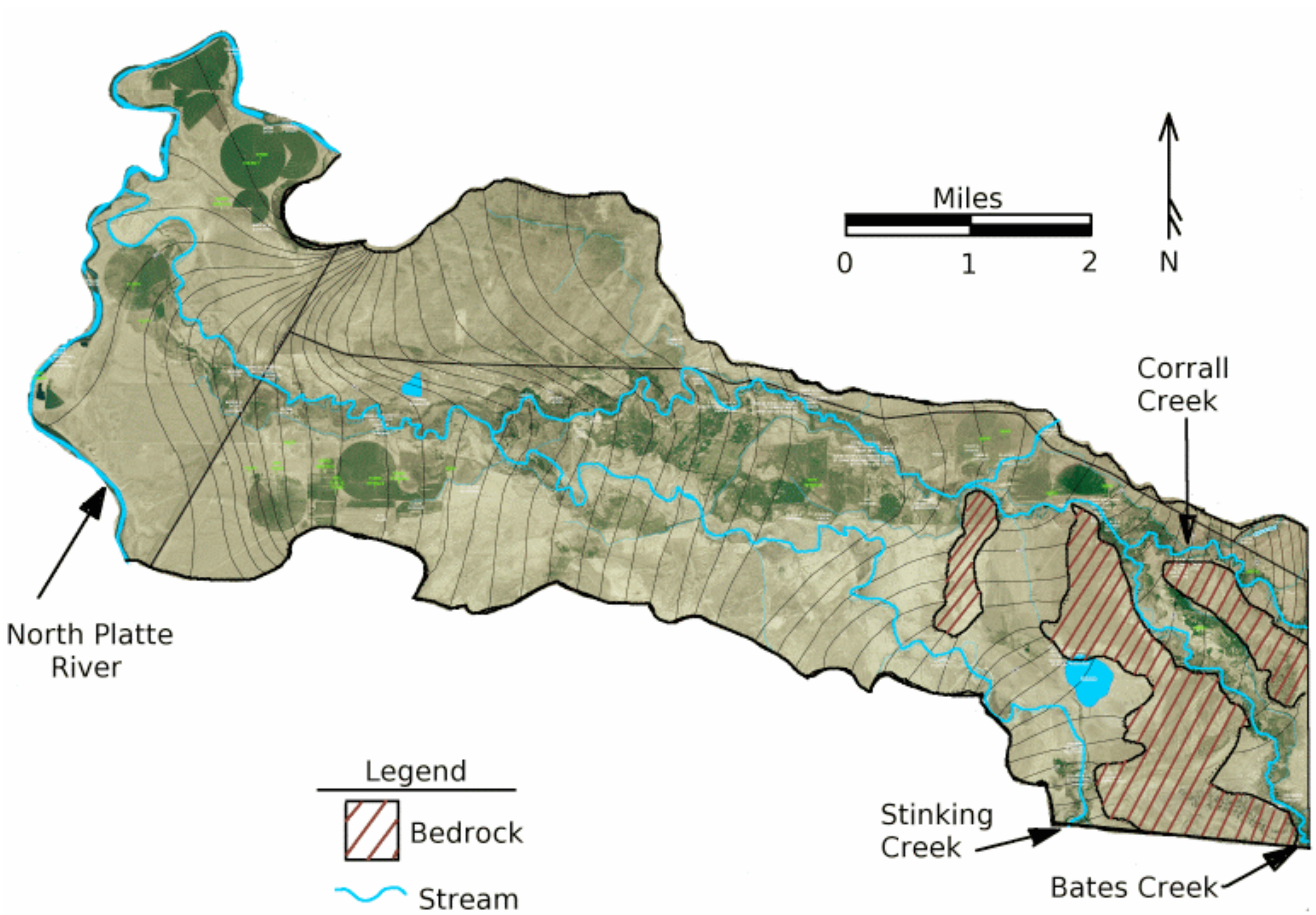

Figure 16: Bates Creek Irrigation District Study Area. The study area is bounded by the North Platte river on the western edge.

Past Studies of the Bates Creek Study Area

A comprehensive field investigation of the Bates Creek study site has not been performed at the time of writing of this report. Therefore, the quantity of data on aquifer properties and surface hydrology is limited. The lack of detailed surface hydrology data, known quantities of surface diversions and groundwater pumping prevent development of an actual conjunctive management plan for this area. Creation of such a plan will require more data than presently exist.

Glover (1983) developed a single-layer (depth-averaged) digital model of the Bates Creek alluvial aquifer using a computer code that is a precursor of the USGS Modflow software. Hydrologic data collected during 1977 and 1978 were used in model calibration. After calibration, the model was run under steady-state and transient conditions for three different scenarios. These scenarios included (1) no ground water pumping, (2) pumping by all existing wells, and (3) pumping by all existing and proposed wells. Simulations used average values of stream discharge, water use, and pumping rates. The simulation results indicated that the quantity of groundwater exfiltration to Bates Creek would decrease throughout the simulated period, which extended until 1988. The numerical study by Glover (1988) did not seek to identify the effect of individual wells on flows in Bates Creek within the context of prior-appropriation water rights doctrine.

Glover (1983) did not perform aquifer tests as part of his study. Rather, he used values of the saturated hydraulic conductivity (*K*) estimated from borehole samples to be in the range of 190 to 900 ft/day. Glover (1983) reported that the saturated thickness in the alluvial aquifer varies from 0 to more than 80 feet. Glover (1983) assumed that the specific yield (S_y) of the aquifer is 0.23, which is the same value found by Crist (1975) in the with the North Platte valley-fill aquifer in Wyoming. Glover (1983) reported that stream bed hydraulic conductivities at two locations were 1.65 x 10^{-5} ft/s and 2.43 x 10^{-5} ft/s. In his modeling study, Glover (1983) used a value equal to the average of these two values, 2 x 10^{-5} ft/s, and assumed that the thickness of the streambed impeding layer was 1 ft.

The digital aquifer simulation code used by Glover (1983) had a minimum grid size of 750 ft, a maximum grid size near the north and south model boundaries of 1,500 ft., and was calibrated against observed water levels. This calibration resulted in identification of saturated hydraulic conductivities on a grid-by-grid basis. Glover (1983) reported a root-mean-squared difference between measured and modeled ground water heads of 2.4 ft. The calibrated saturated hydraulic conductivity field is lost. Glover (1983) reported that his calibrated model was insensitive to variations in the specific yield parameters in the range of 0.20 to 0.25.

In transient simulations, Glover (1983) reported that groundwater depletions were not completely re-filled during the non-irrigation season. This result indicated that there is a “memory” in the system that is longer than one-year. As such, streamflow depletions will continue to increase over time due to the effect of pumping wells.

The primary limitations on the study reported by Glover (1983) are uncertainties in stream inflow and diversion rates. Average values of these inputs were used over the 10-year prediction period from 1979-1988. Because of this, there is considerable uncertainty in the meaningfulness of the numerical model results. The study by Glover (1983) did not consider the impact of pumping of individual wells.

Langstaff (2006) applied the analytical Glover-Balmer technique (Glover and Balmer, 1954; Jenkins, 1968) to investigate the effect of pumping of individual wells on stream flow depletions. Langstaff relied upon the parameters published in the Glover (1983) report. Results of this analytical methodology show how the irrigation wells in the Bates Creek alluvial aquifer have an effect on surface flows, the significance of this effect varies with pumping rate and distance from the creek. As expected, the effect is largest for wells that are pumping more water from the aquifer, and for those wells that are closest to the creek. The analytical method also shows that due to the "lag effect of distance" wells that are far from the creek can increase surface depletions weeks to months after those wells are turned off.

Langstaff (2006) writes that the results of his analytical study cannot be relied upon in detail. While Langstaff (2006) does not give detailed reasons for this statement, it is clear that the analytical methodology does not fully consider recharge from precipitation and irrigation, nor the interaction between wells.

Modeling Framework

The modeling framework we developed uses the USGS *MODFLOW* model for groundwater simulations and the Ground Water Management (*GWM*) optimization software to address management questions. Setting up the modeling framework requires the following steps:

1) Study area delineation and discretization

2) Locating available input hydrologic, ground water, diversions, pumping, land surface, channel, and climate forcing data

3) Development of *MODFLOW* steady-state stress period input files

4) Steady-State *MODFLOW* calibration using PEST against groundwater monitoring well data to estimate the aquifer hydraulic conductivity field

5) Development of *MODFLOW* unsteady stress period input files (based on meteorological and flow data, and observations of variable diversions and pumping rates)

6) Run transient simulations within *GWM* simulator to evaluate the sensitivity of streamflow discharges at diversion points to different time-series combinations of well pumping

7) Interpretation of results

Fig. 17 shows a flow-chart of the modeling framework that would be used to develop a management plan. There is no established methodology for developing the test scenarios in the context of prior-appropriation water rights. In this case we developed a method based on available surface flows as discussed in a later section.

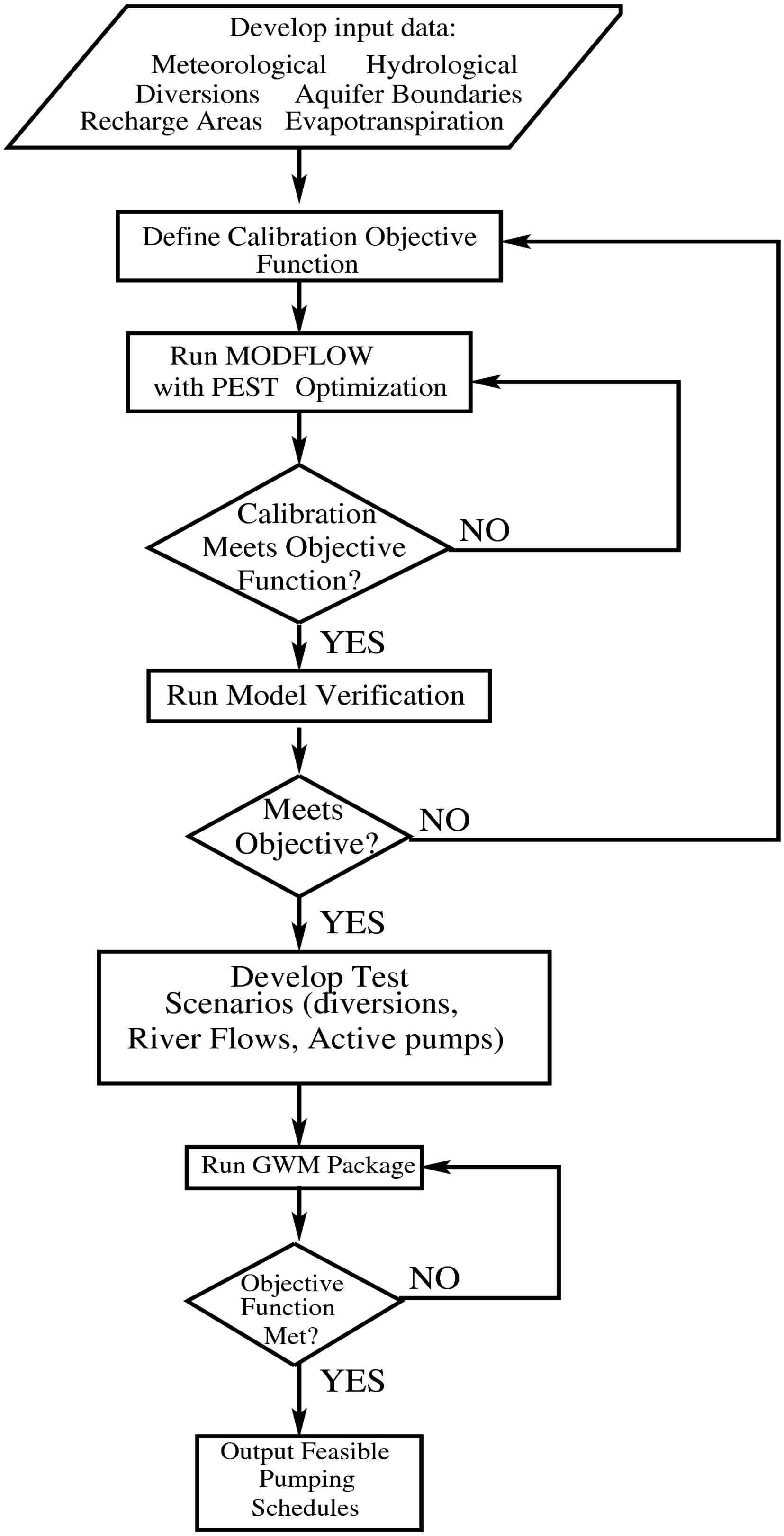

Figure 17: Modeling framework flow chart.

Groundwater wells are used in the Bates Creek study area for irrigation. Fig. 18 shows the location of the wells considered in this study. The wells are labeled Q1 through Q16, and their location coordinates and permitted pumping rates are listed in Table 2. Irrigation recharge areas are shown as green polygons. Headgates for surface water diversions are labeled G1 through G6.

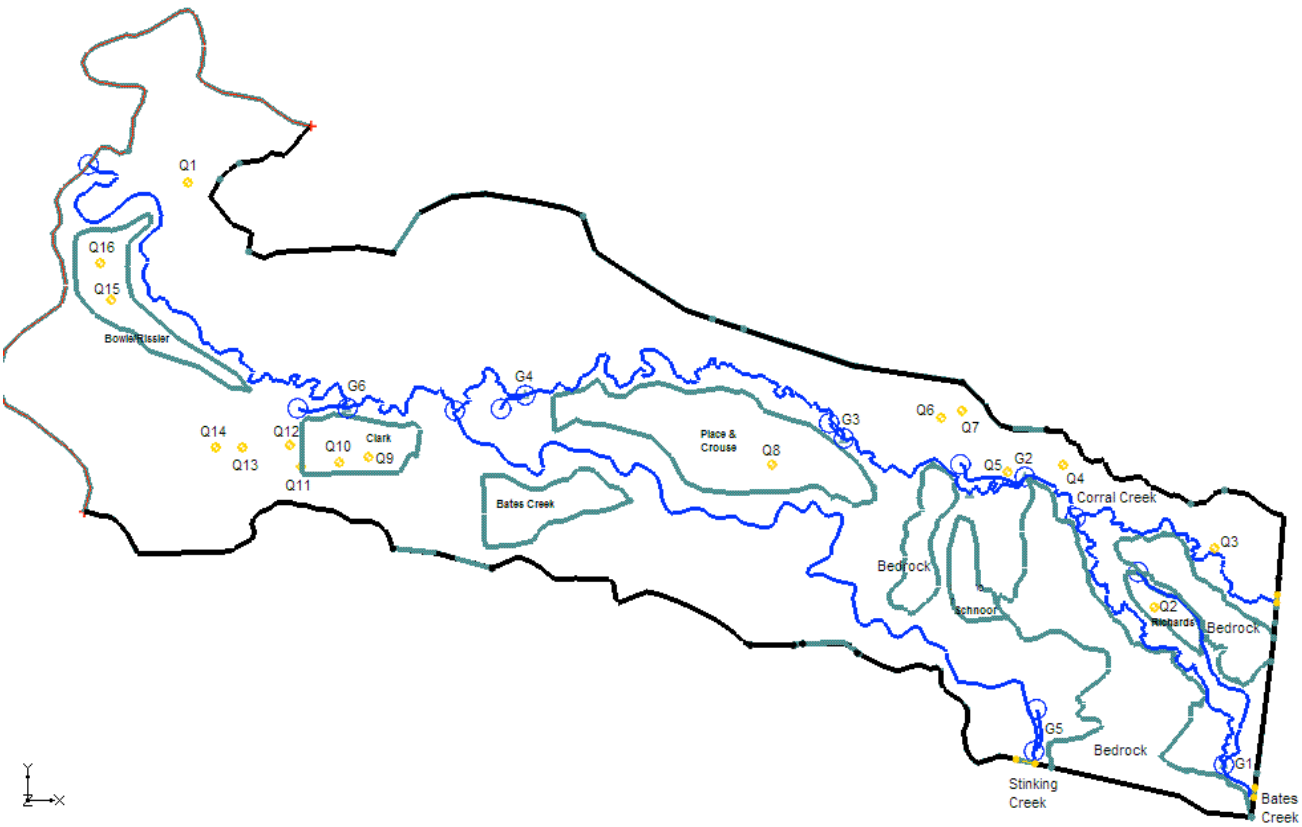

Figure 18: Location of wells and irrigation recharge areas within the study area.

Table 2. Permitted Wells in the Study Area

Permit No.	Well No.	Permitted Discharge (gpm)	row	column	Easting	Northing
62305	Q1	375	33	31	1509642	1127005
26060	Q2	950	84	123	1553418	1108037
28878	Q3	925	77	129	1556141	1110693
38044	Q4	1300	67	114	1549283	1114389
3622	Q5	875	68	109	1546779	1114071
38042	Q6	1100	62	103	1543778	1116507
38043	Q7	650	61	105	1544707	1116824
3995	Q8	1175	66	86	1536094	1114425

10364	Q9	1200	64	47	1517583	1114712
10365	Q10	1550	65	45	1516507	1114496
402	Q11	700	65	41	1514780	1114310
83022	Q12	150	63	40	1514253	1115271
111934	Q13	1550	63	35	1512113	1115178
111933	Q14	650	63	33	1510899	1115186
111471	Q15	500	46	23	1506161	1121760
111472	Q16	425	42	22	1505674	1123424

***MODFLOW* Steady State Calibration**

Data from Glover (1983) were used to calibrate the *MODFLOW* model. The PEST parameter estimation scheme (Doherty 2003) within *GMS* was used with pilot points to estimate the saturated hydraulic conductivity field. Results of the calibration at monitoring points are shown in Fig. 19.

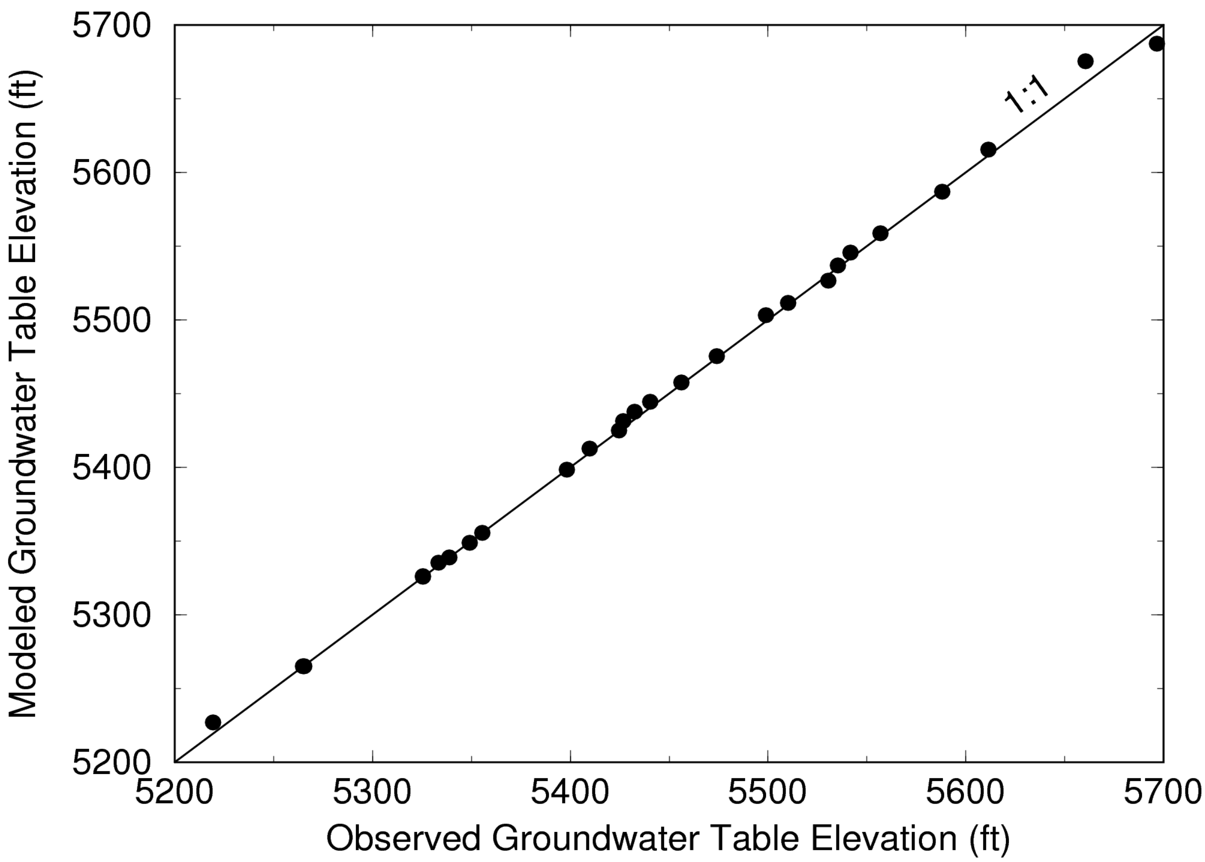

Figure 19: Agreement between observed and calibrated steady-state water table elevations, using data from Glover (1983).

Calibrated groundwater heads are shown in Fig. 20 with error bars shown at the locations of well data used in calculating the calibration objective function. Note that only two wells have significant deviations, both in the far north-east corner of the active domain. These two wells are in a region of steep groundwater table gradient. These wells are quite close together, with opposite sign on the error, indicating some local deviations in aquifer properties not captured by the *MODFLOW* model. The root mean square error of the calibrated heads, excluding the two wells in the north-east corner of the domain is 2.46 ft.

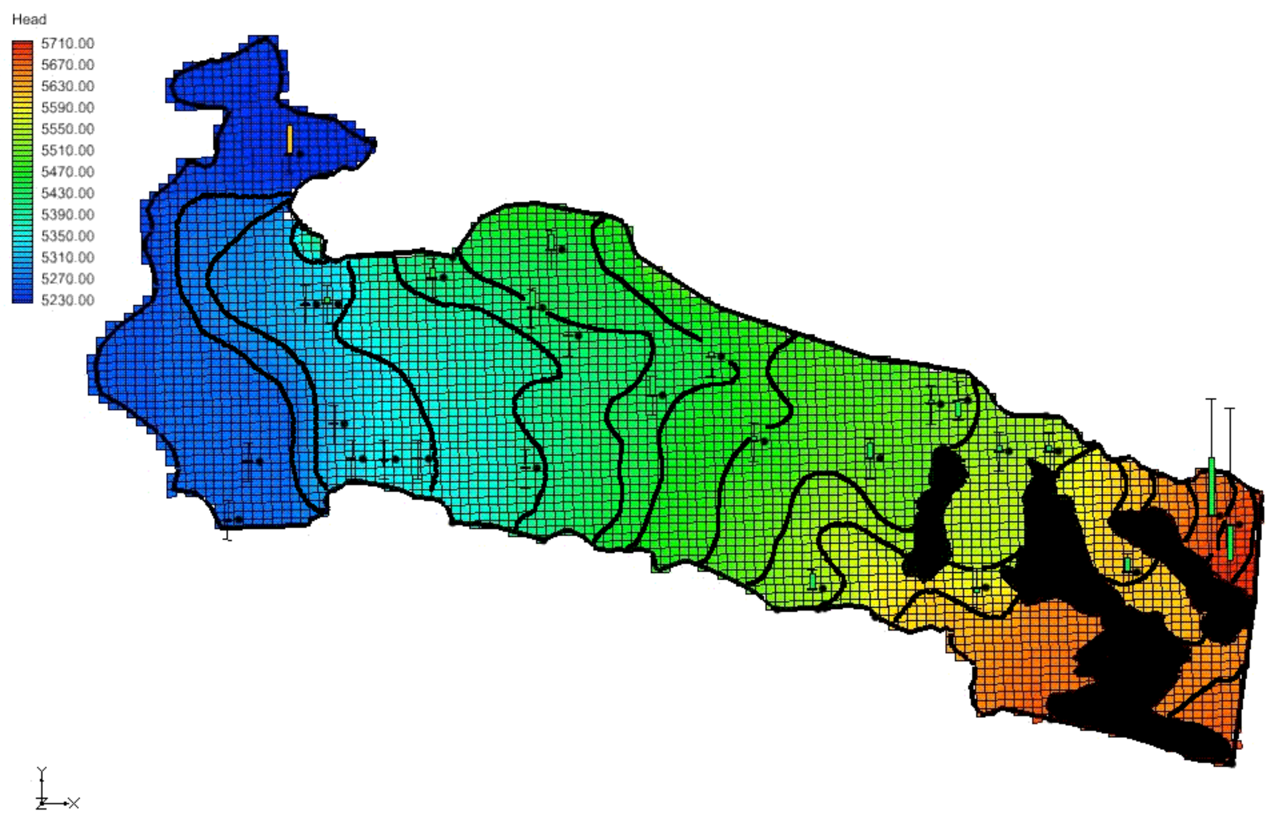

Figure 20: Calibrated steady state phreatic surface in study area. Black areas are bedrock. Error bars show calibration efficiency at monitoring wells using data from Glover (1983).

Test Scenarios

The prior-appropriations water rights doctrine imposes a set of constraints that are not typical for many groundwater pumping optimization scenarios outside of the Western U.S. The overall objective of the optimization is to maximize groundwater pumping while minimizing streamflow depletions as to not impact senior surface water rights. The class of senior water rights also have their own priorities that must be respected. In this demonstration, we considered the surface water rights listed in Table 3 obtained from the Wyoming Water Resources Data System on-line map server (http://ims2.wrds.uwyo.edu/Website/Statewide/viewer.htm, accessed Dec. 8, 2009). The quantities of water associated with each diversion were estimated, and are used in this demonstration as examples. The values listed in Table 3 <u>do not</u> represent actual diversion amounts approved by the water commissioner, and are used here for model framework testing only. It is up to the State water management agency to determine the appropriate amounts for each diversion. This list is also not exhaustive, but it contains most of the major surface water diversions in the study area.

Table 3. Assumed irrigation diversions at six major canal headgates in study area.

Div. No.	Ditch	Permit Date	Priority	Est. acre-feet per year	Maximum diversion during irrigation season (cfs)	*MODFLOW* input cubic feet per day
1	Richards Ditch	05/01/1888	3	1530	4.19	362,211
2	Place & Crouse Ditch	5/30/1896	4	1060	2.9	250,943
3	Bates Creek Ditch	03/14/1886	1	4500	12.33	1,065,326
4	Clark Ditch	06/18/1896	5	1490	4.08	352,741
5	Schnoor Ditch	05/15/1908	6	467	1.28	110,557
6	Bowie and Rissler Ditch	09/08/1886	2	2840	28,672	672,339

It is very important that the reader of this report understand that the surface diversions listed in Table 3 were used in this demonstration of the modeling framework as an example and are not actual values. In reality, the surface water rights in the Bates Creek area are more complex due to modifications to some diversions over time, and distinctions in the data base that require more detailed understanding of their meaning than the on-line database provides. The actual diversions allowed by the water commissioner should be used in the actual application of this modeling framework.

In developing our test cases, we decided upon six scenarios. These scenarios depend on whether or not there is sufficient flow in Bates Creek where it enters the model domain to support all six surface water diversions, or the most senior 5, 4, 3, 2, or 1 surface water rights. Our motivation in using these scenarios is unique to prior appropriations water rights doctrine. For instance, if there is only sufficient water in Bates Creek to support the most senior water right in the study area, the Bates Creek ditch, then it is impossible that groundwater pumping would impair the other five un-satisfied surface water rights as determined by surface measurements. This creates a conundrum for the water manager, as it raises the issue "Should junior ground water wells be allowed to pump while senior surface water rights are unmet?" The test cases used in this demonstration are listed in Table 4. Because we were lacking hydrologic data in Stinking and Corral Creeks, flows were assumed and held fixed at 1.27 and 3.10 cfs, (110560 cfd and 267840 cfd), respectively.

Table 4. Flow rates used in demonstration scenarios.

Scenario	Headgate Diversions (cfs) Number corresponding to Diversion No. in Table 3.						Bates Creek Inflow (cfs)
	1	2	3	4	5	6	
1	4.19	2.9	12.33	4.08	1.28	7.78	19.21
2	4.19	2.9	12.33	4.08	-	7.78	17.95
3	4.19	2.9	12.33	-	-	7.78	12.95
4	4.19	-	12.33	-	-	7.78	11.23
5	-	-	12.33	-	-	7.78	7.84
6	-	-	12.33	-	-	-	7.14

***MODFLOW* Stress Periods**

The *MODFLOW* simulation consisted of six stress periods spanning 11 months. The first stress period persisted for 182 days during the non-growing season, and represented a steady-state solution. The remaining five stress periods, each represented one month, for the months of May through September, and representing the growing-season. In the case where all surface water diversion rights were met during the entire growing season, the following flows were assumed in Bates Creek during the six stress periods:

Table 5. Assumed Bates Creek flows during different stress periods to insure that all assumed surface diversions were met without ground water pumping in Scenario 1.

Stress Periods	Bates Creek Flow (cfs)	Bates Creek Flow (cfd)
1	13.8	1,592,000
2	13.8	1,592,000
3	19.53	1,687,000
4 through 6	19.21	1,660,000

In this demonstration 70% of irrigation diversions were placed uniformly on the fields irrigated by each ditch as groundwater recharge. The fields are denoted by polygons and shown in Fig. 3. This assumes that 30% of the irrigation water applied in flood irrigation is consumed by evapotranspiration. We did not perform a detailed analysis of this percentage, as site-specific values will be needed.

Application of *GWM*

For the Bates Creek study, *GWM* imposes constraints on streamflow, as simulated using the SFR package (Prudic and other, 2004), to insure that adequate flow exists in the stream to allow specified diversions at gates. Binary variables are used in conjunction with flow-rate variables to determine the maximum amount of groundwater pumping that can be achieved while maintaining adequate streamflow. The problem is formulated so that a pumping decision is made in each month of the irrigation season (end of May, June, July and August) for each of the 16 pumping wells. The pumping decision is binary, that is, *GWM* decides if the pump should be on or off. If the pump is on it operates at a rate that is a function of the permitted pumping rate for that well. The objective function in the Bates Creek formulation is to maximize the total withdrawal from all wells over the irrigation season. This is equivalent to maximizing the sum of flow-rate variables weighted by the duration of pumping for each well.

Results from the *GWM* runs with the Bates Creek simulation model reveal the complexity of the relationship between pumping and stream flow. While an intuitive response to inadequate streamflow at a gate may be to cut pumping at the nearest well, the *GWM* results show that this is often not the best strategy. Pumping early in the season can have impacts on downstream gate flows late in the season. Pumping far upstream from the affected gate has an impact on both groundwater delivery in the current month and later months and on stream delivery of water to downstream gate in the current month.

The relationship between pumping and stream flow at a gate is quantified by *GWM* through response coefficients. These values give the change in stream flow at a surface diversion point per unit change in pumping at a well. *GWM* calculates these response coefficients for every combination of 24 stream flows (4 months at each of 6 gates) and 64 pumping rates (4 months at each of 16 wells) for a total of 1536 response coefficients. Figure 21 gives an example of the *GWM* output from the Bates Creek demonstration, which shows the effect of pumping of all wells on stream flow the Bates Creek Ditch headgate (gate no. 3) under test scenario 6.

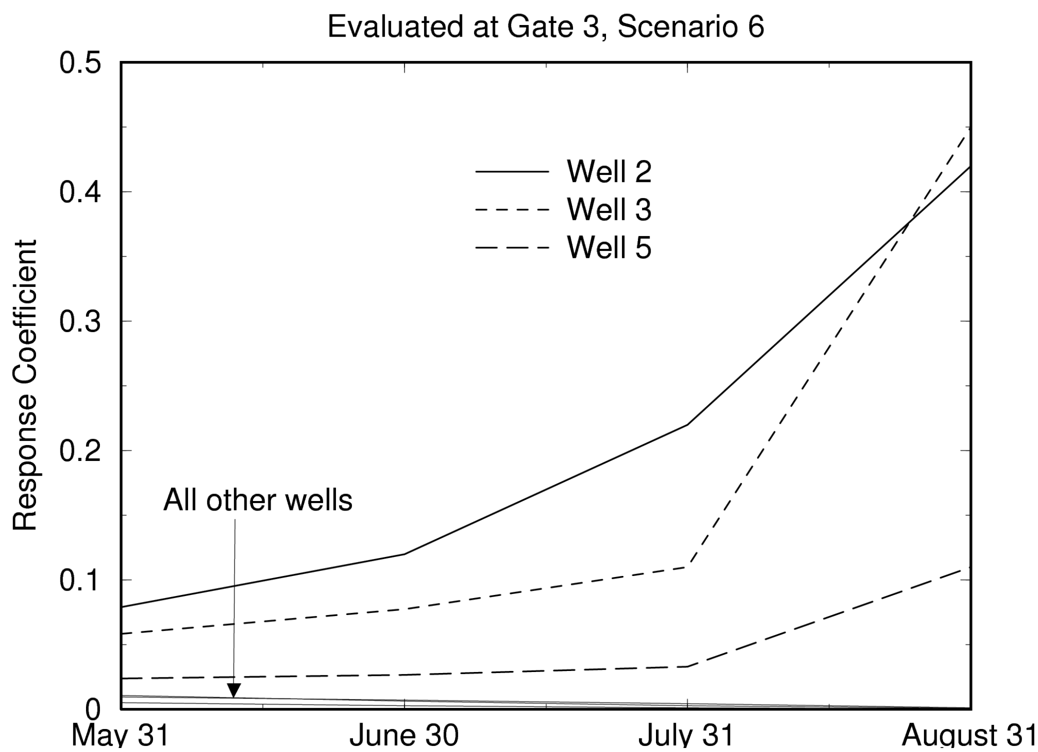

Figure 21: GWM Response Coefficients evaluated at the Bates Creek Ditch headgate for scenario 6.

GWM uses the calculated response coefficients to determine the combined impact of all wells pumping simultaneously on stream flows at all gates. This information is, in turn, used to determine the optimal combination of pumping rates that maximizes groundwater withdrawals while guaranteeing adequate stream flows for diversions for a given stream flow at the model domain boundary. For example, for the Scenario 6 results shown in Fig. 21, in order to insure that adequate water is present at the Bates Creek Ditch diversion, *GWM* determines that the best strategy is to turn off wells 2, 3 and 5. Note that wells 2 and 3 are the furthest upstream wells and farther from the diversion than 3 other wells (4, 6, 7) that are left on by *GWM*. Also note that the effect of pumping well 3 is intermediate early in the growing season, but the effect of pumping this well increases over the irrigation season, until it has the largest effect on headgate no. 3 at the end of August.

Conclusions

This report presents a model framework developed using readily available computational tools that can be used to identify a conjunctive-use management strategy. The tools used include the Groundwater Modeling System (*GMS*) model interface, USGS *MODFLOW* groundwater simulator and USGS *GWM* optimization code. As this study did not include collection of field data, we used data collected by others. The Wyoming State Engineer's office recommended that we demonstrate our modeling framework on the Bates Creek irrigation district southwest of Casper, Wyoming, near the confluence of Bates Creek and the North Platte River. The Wyoming State Engineer's office provided data for this area, and we used the previous modeling report by Glover (1983), for guidance on parameter values.

Before application of this modeling framework to a specific region, including the Bates Creek site used in this study, data collection is a necessity. Field studies in areas of interest should focus on collecting hydrologic data for a multi-year period in order to allow model calibration and verification over a range of seasons and climatic variation. These data would include stream flows, canal diversions and schedules, actual groundwater pumping flow rates and schedules, groundwater observation/monitoring wells, precipitation, snow melt, and meteorological variables.

Other parameters such as stream/canal bed infiltration losses and impeding layer properties are needed, as are observations of groundwater levels near streams. Land-surface data required include irrigation recharge areas, crops, rates of irrigation and times of application. These data together with the meteorological observations will allow estimation of consumptive use, leaching fraction, and groundwater recharge from irrigation. If surface return flows from irrigation are significant, they should be measured.

Studies and efforts underway to develop conjunctive management schemes in Nebraska and Colorado on this issue cover large irrigation areas near large rivers. Those efforts are quite expensive. While the cost for setting up an actual conjunctive management modeling tool on a specific irrigation district in Wyoming will be less, the need for data is the same. Without data, the modeling tool cannot be calibrated and verified.

We identified test scenarios based on the number of surface water diversions that could be satisfied given surface flows, based upon seniority. This is a unique aspect of this management problem. Management can only be performed to the degree that surface flows allow. In the absence of pumping, if there is only sufficient surface flow to meet the demands of a senior subset of surface diversions, it is nonsensical to manage pumping to optimize surface water diversions that cannot be met due to priority. To our knowledge, there is no widely accepted method to account for the effect of surface water priorities in an optimization scheme.

Our methodology assumes that all ground water rights in the study area are junior to all surface water rights. We did not take the date of well permitting into account in minimizing the impacts of individual wells on stream flow depletions. In effect, if any well is causing stream flow depletions that impinges on any surface water right, it must be shut off.

The GWM response coefficients indicate that in some cases, a well that is further from the stream diversion point can have a more significant and long-term effect on surface water diversions than a well that is closer to the diversion point. In this demonstration, there were instances when a well far from the stream had a significant effect on stream flow at a downstream location, later in the irrigation season. This example illustrates the utility of the approach.

References Cited in Part 2.

Ahlfeld, D.P., Barlow, P.M., and Mulligan, A.E., 2005, GWM—A ground-water management process for the U.S. Geological Survey modular ground-water model (MODFLOW-2000): U.S. Geological Survey Open-File Report 2005-1072, 124 p.

Ahlfeld, D.P., Baker, K.M., and Barlow, P.M., 2009, GWM-2005—A Groundwater-Management Process for MODFLOW-2005 with Local Grid Refinement (LGR) capability: U.S. Geological Survey Techniques and Methods 6–A33, 65 p.

Ahlfeld, D.P., and Heidari, Manoutchehr, 1994, Application of optimal hydraulic control to ground-water systems: Journal of Water Resources Planning and Management, v. 120, no. 3, p. 350–365.

Ahlfeld, D.P., and Mulligan, A.E., 2000, Optimal management of flow in groundwater systems: San Diego, CA, Academic Press, 185 p.

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, no. 1, 32-53 pp.

Aquaveo, 2010, URL http://www.aquaveo.com/gms, accessed 22 April, 2010.

Argus ONE, 2010, URL http://www.argusint.com/GroundWater.html accessed 22 April, 2010.

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, pp. 35-48.

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.

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. 125, no. 3, 154-161 pp.;

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.

Bergfeld, L. G., 2005. Investigative study of conjunctive use opportunities in the Stony Creek Fan Aquifer. Thesis Submitted in Partial Satisfaction of the Requirements for the Degree of Master of Science in Civil Engineering in the Office of Graduate Studies of the University of California, Davis, California.

Bryner, G. and Prucell, P., 2003, *Groundwater Law Sourcebook of the Western United States*. Natural Resources Law Center, 83 pp.

Cannia, J. 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.

Carney, C. 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.
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, pp. 251-275.
Correa, N. R., 1990. Optimal operation strategies for groundwater reservoirs - consideration of quantity and quality aspects. International Association of Hydrological Sciences. Pp. 11-17; 11 refs. Wallingford, Oxfordshire OX10 8BB, United Kingdom: IAHS Press, Institute of Hydrology.
Cosgrove, D. M. and G. 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.
Crist, M.A., 1975, Hydrologic analysis of the valley-fill aquifer North Platte River valley, Goshen County, Wyoming: U.S. Geological Survey Water-Resources Investigations 75-3, 60 pp.
Doherty, J., 2001, Improved calculations for dewatered cells in MODFLOW, Ground Water 39(6), pp. 863-869.
Doherty, J., 2003. Groundwater model calibration using pilot points and regularisation. *Ground Water*. 41 (2): 170-177.
Dvorak, A, 2000, Central Valley Groundwater Bank Operations: Hydrology, Groundwater Operating Rule, ad System Operating Rule Effects on Yield, M.S. Thesis, University of California, Davis, 56 pp.
Fleckenstein, J.H., R. G. Niswonger, and G.E. Fogg, 2006, River-Aquifer Interactions, Geologic Heterogeneity, and Low Flow Management, *Ground Water*, Special issue from MODFLOW and more conference, 2003.
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 (2), 69-78 pp.
Glover, K.C., 1983, Digital model of the Bates Creek alluvial aquifer near Casper, Wyoming, U. S. Geological Survey Water-Resources Investigations 82-4068, 45 pp.
Glover, R.E. and Balmer, G.G., 1954, River depletion resulting from pumping a well near a stream: Trans. American Geophysical Union, 35(3), p. 468-470.
Gorelick, S.M, 1983, A review of distributed parameter groundwater management modeling methods: Water Resources Research, v. 19, no. 2, p. 305–319.
Gorelick, S.M., Freeze, R.A., Donohue, David, and Keely, J.F., 1993, Groundwater contamination—Optimal capture and containment: Boca Raton, FL, Lewis Publishers, 385 p.
Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.
Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.
Henszey, R. J., K. Pfeiffer, and J. 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.
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.
Jenkins, C.T., 1968, Techniques for computing rate and volume of stream depletion by wells: Ground

Water, v. 6(2), p. 37-46.
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, pp. 271-280
Jobson, H.E. and Harbaugh, A.W., 1999, Modifications to the diffusion analogy surface-water flow model (DAFLOW) for coupling to the moddular finite-difference ground-water flow model (MODFLOW): U.S. Geological Survey Open-File Report 99-217, 107 p.
Krapu, G. 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.
Kress, W. H. and others, 2004. Use of continuous seismic profiling to differentiate geologic deposits underlying selected canals in central and western Nebraska. USGS Fact Sheet 115-03. Pp. 1-6. U.S. Geological Survey.
Kress, W. H., B. J. Dietsch, and J. 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.
Landon, M. 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.
Langstaff, G, 2006, Stream depletion due to irrigation wells along Bates Creek, Natrona County, unpublished report, obtained from Wyoming State Engineer's office, 9 pp.Knapp, K. C. and L. J. Olson, 1995. The economics of conjunctive groundwater management with stochasticsurface supplies. *Journal of Environmental Economics and Management* Vol. 28, no. 3, 340-365 pp.
Lewis, G. L. and D. 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.
Marino, M. A., 2001. Conjunctive management of surface water and groundwater. 165-173 pp. Wallingford, UK: IAHS Press.
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.
McHugh, K. 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.
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, 201-221 pp.
Meselhe E.A. and Holly F.M. Jr. (1997). Invalidity of the Preissmann scheme for transcritical flow, *J. Hydraul. Engrg.*, ASCE, vol. 123 (7).

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

Morel-Seytoux, H. J., 2001. Value and modeling of conjunctive use of surface and groundwaters in basin management. 183-190 pp., Wallingford, UK: IAHS Press.

Nadim, F., A. Bagtzoglou, S. Baun, G.S. Warner, F.L. Ogden, R. A. Jacobson, P. Parasiewicz, 2007, Management of Adverse Effects of a Public Water Supply Well Field on Aquatic Habitat of a Stratified Drift Stream in Eastern Connecticut, *Water Envir. Res*., 79(1):43-56.

Niswonger, R.G., Prudic, D.E., and Regan, R.S., 2006, Documentation of the Unsaturated-Zone Flow (UZF1) Package for modeling unsaturated flow between the land surface and the water table with MODFLOW-2005: U.S. Geological Techniques and Methods Book 6, Chapter A19, 62 p.

Niswonger, R.G. and Prudic, D.E., 2005, Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams--A modification to SFR1: U.S. Geological Survey Techniques and Methods, Book 6, Chap. A13, 47 p.

NRC, 2000, Investigating Groundwater Systems on Regional and National Scales, National Academy Press, 2101 Constitution Avle, N.W., Washington, D.C., 20418.

Onta, P. R. and others, 1991. Integrated irrigation development planning by multi-objective optimization. *International Journal of Water Resources Development* Vol. 7, no. 3, 185-193 pp.

Painter, S., Basagaoglu, H., and A. Liu, 2008, Robust representation of dry cells in single-layer MODFLOW models, Ground Water, 46(6), pp. 873-881.

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, December 15-16, 1986.

Peralta, R. C., A. Gharbi, L.S. Willardson and A.W. Peralta, 1990 (rev. 1992) Optimal conjunctive use of ground and surface waters, Xhapter 12 of Management of Farm Irrigation Systems, ASAE, pp. 426-458.

Peterson, S. 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.

Philbrick, C. R. and P. K. Kitanidis, 1998. Optimal conjunctive-use operations and plans. *Water Resources Research*, Vol. 34, no. 5, pp. 1307-1316.

Prudic, D.E., Konikow, L.F., and Banta, E.R., 2004, A new stream- flow routing (SFR1) package to simulate stream-aquifer interaction with MODFLOW-2000: U.S. Geological Survey Open-File Report 2004-1042, 95 p.

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 (3), W03401 p.

Pulido-Velasquez, M., J. Andreu, and A. Sahuquillo, 2006, Economic Optimization of Conjuctive Use of Surface Water and Groundwater at the Basin Scale, *J. Water Resour. Plng. and Mgmt*, 132(6):454-467.

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

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

Rus, D. L. and others, 2002. Streambed hydraulic conductivity in Central and Western Nebraska. The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangeed 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.

Schaffranek, R.W., 1987, Flow model for open-channel reach or network: U.S. Geological Survey Professional Paper 1384, 12 p

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.

Schmidt, W., T. Maddock III, and S.A. Leake, 2006. User Guide for the Farm Process (FMP1) for the U.S. Geological Survey Three-Dimensional Finite-Difference Ground-Water Flow Model, MODFLOW, U.S. Geological Survey, Techniques and Methods 6-A17.

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, pp. 15-31; 40 ref.

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

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.

Silka, L. R. and A. G. Kretschek, 1984. Incorporation of Predicted Future Climatic Effects into Simulations for Ground Water Resource Evaluations. Pp 286-294, 7 fig, 1 tab, 24 ref. Proceedings of NWWA Western Regional Conference on Ground Water Management. San Diego, California; October 23- 26, 1983. Worthington, OH: National Water Well Association.

Stansbury, J. and others, 1991. Decision Support System for Water Transfer Evaluation. *Water Resources Research* Vol. 27, No. 4, pp. 443-451.

Tellman, B., 2003. *Why Has Integrated Management Succeeded in Some States But Not Others?* Water Research Center, University of Arizona (on file with the author), p. 15.

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

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, pp. 14-24.

Willis, R., and Yeh, W.W.-G., 1987, Groundwater systems planning and management: Englewood Cliffs, NJ, Prentice-Hall, 416 p.

Wilson, L. and S. Anderson, 2006, Development of a Conjunctive Use Management Plan for the Central Platte Valley - Task 3A: Case Studies, Report by Lee Wilson and Associates, Inc., accessed at http://dnr.ne.gov/PlatteRiver/docs/reports.html, 18 April, 2010.

Woessner, W.W., 2000, Stream and Fluvial Plain Ground Water Interactions: Rescaling Hydrogeologic Thought, *Ground Water*, V38, No. 3, pp. 423-429.

Yan, J. and K. R. Smith, 1994. Simulation of integrated surface water and ground water systems - Model formulation. *Water Resources Bulletin* Vol. 30, no. 5, pp. 879-890.

Yeh, W.W.-G., 1992, Systems analysis in ground-water planning and management: Journal of Water Resources Management and Planning, v. 118, no. 3, p. 224–237.

Young, R. A., 2005. Determining the Economic Value of Water, Concepts and Methods. 357 pp. Washington, DC: Resources for the Future.

Zhang, C.-M., 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 State University, Fort Collins, CO 80523 (USA): Colorado Water Resources Research Institute.

Appendix A

Telephone Script for Interviews

"Integrated Management of Groundwater and Surface Water Resources: Investigation of Different Management Strategies and Testing in a Modeling Framework"

Hello, I am __________, a research assistant for Melinda Harm Benson, an assistant professor at the University of New Mexico. She is conducting research on how different states manage ground and surface water resource issues. You have been identified as someone with expertise in the area of conjunctive water resource management. We are doing some interviews for a report that will be presented to the State of Wyoming's State Water Engineer.

All information gathered during this interview will be kept confidential. If you would like additional information about how we intend to protect your privacy or about this research, you can contact Professor Benson at 505-277-1629, or you can email her at mhbenson@unm.edu.

Would you be willing to answer a few questions regarding on this topic?

If "no:" "thank you for your time. Goodbye." (then hang up).

If "yes": "Great, here are my questions—they need only take10 minutes or so of your time."

4) What has been your experience with your state's attempt to conjunctively manage ground and surface water resources and/or address conflict between surface and ground water users?
    1. Would you describe the experience as positive, negative?
    2. Why or why not?

5) Do you have any suggestions for how your state could improve its management of ground and surface water use conflicts?

6) Can you provide any examples of specific ground and surface water interactions in your state that inform your answers to questions 1 and 2?

7) What, in your opinion, is the greatest barrier to effective conjunctive management in your state?

8) Do you feel like your state has the necessary technical/hydrologic information necessary to implement its management scheme? Why or why not? What would improve the situation?

9) Is there anything else you would like to tell us about your experience with your state's management of ground/surface water use conflicts?