EFFECT OF WATER RIGHTS AND MANAGEMENT POLICIES ON A RIVER ALLUVIAL AQUIFER

By

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EFFECT OF WATER RIGHTS AND MANAGEMENT

POLICIES ON A RIVER ALLUVIAL AQUIFER

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CHAPTER 1

INTRODUCTION

Water is an invaluable resource and will become even more so in the coming years. Water shortages have been affecting people in the arid west for several years and in drought years the people in the east have recently seen that they are not immune. Due to urbanization and climate change, water shortages are expected to increase in the future. There are some tools such as water conservation, reuse, harvesting, and metering that are effective throughout the U.S. in managing water resources.

The manner in which surface and ground water are allocated varies considerably across the United States. In general, the humid eastern states use the riparian doctrine and the arid western states have adopted the doctrine of prior appropriation. Several states with a mixed climate have taken characteristics from both systems of allocation and therefore have a hybrid system. This paper reviews the ways Arkansas, Oklahoma, Texas, and New Mexico allocate surface and ground water and how they treat the ground-surface water interaction. Arkansas represents the humid east, New Mexico represents the arid west, and Oklahoma and Texas represent hybrid systems where the climatic transition takes place. Each state, depending on its water allocation system, has different water management tools available to them.

Each state has adopted specific rules and regulations stating how it allocates its water resources, and therefore they handle water rights and shortages differently. Even among the states with the same allocation system, there are several differences. Arkansas, Oklahoma, Texas, and New Mexico are no exception.

When considering water policy decisions, Oklahoma has the option of reviewing the water policies of other states, especially those with similar climatic conditions. There are several policies that Arkansas, Texas and New Mexico have implemented that may be used to improve the current policies in Oklahoma and to help prepare for future water shortages due to urbanization and climate change. Interesting alternatives include metering in Arkansas, water masters in Texas, and water master districts and priority-administration enforcement in New Mexico.

I chose the ground water rules and regulations of Oklahoma and the Texas Panhandle Groundwater Conservation District (GCD) to study in more detail. Though both Oklahoma and Texas have a hybrid system of water allocation, they permit the use of ground water in two distinct ways. Oklahoma sets its ground water allocations based on a one-time estimate of the pumping rate that would allow 50% of the aquifer to go dry after 20 years. The TX Panhandle GCD policy is based on an iterative process that assures 50% of total aquifer storage will remain in 50 years. An important difference between the two policies is that the Panhandle GCD revisits the quantity of ground water permitted every five years, where the Oklahoma permits remain constant.

The objective of this thesis was to compare the effects that Oklahoma's and the Panhandle GCD's groundwater policies have on an alluvial aquifer after 20 and 50 years of pumping with increasing aquifer development. The United States Geological Service (USGS) model MODFLOW was used to complete the simulations. The study further analyzed sensitivity of various aquifer and stream parameters on total aquifer storage and river leakage. The results of this sensitivity analysis demonstrated which parameters are most important to study and determine when completing a stream-aquifer study and model.

CHAPTER II

COMPARISON OF THE WATER RIGHTS OF ARKANSAS, OKLAHOMA, TEXAS, AND NEW MEXICO

Background

Water is tomorrow's new black gold. It is something many of us take for granted until we experience a long drought and realize that there is a finite amount of water. Most of us simply turn on the faucet and presto we have water. Where does that water come from? Depending on where you live, it either comes from surface water such as a river or lake or from the ground. There is the same amount of water on Earth now as there was three billion years ago: 326 million trillion gallons. This seems like a lot, but 97% is in the oceans and not suitable for drinking. Of the remaining 3%, approximately two-thirds are locked up in glaciers, and therefore, less than 1% is available to us as either surface or ground water. There is many times competition to use this finite resource. The same water may be sought by farmers, municipalities, factories, power plants, boaters, fisherman, ecologists, etc.

"Water rights" refers to the rights of the users to take water from a water source and use it or sell it. At times when there is plenty of water and small demand, there is generally not much concern over water rights. At other times, especially in arid areas or where there is much demand, there are more conflicts as to who has the right to the water. There are two divergent systems: riparian doctrine and doctrine of prior appropriation

Each state has adopted one or the other or a combination of the two (Figure 1).

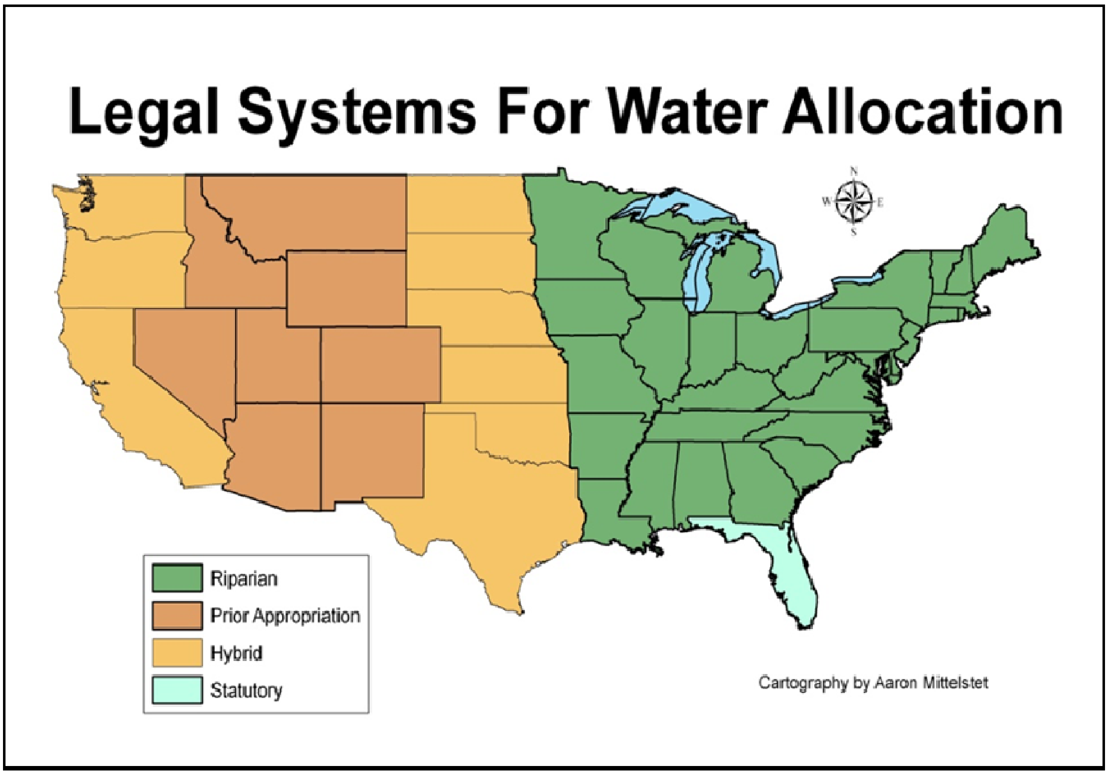

Figure 1. Legal systems of water allocation in the United States

Riparian water rights belong to those landowners whose land physically touches a river, pond, or lake. The riparian landowner has the right to the water, but it may not be unreasonably detained or diverted, as defined by state law or regulations. The definition of reasonable varies from state to state. Riparian rights are not lost if the water is not used and do not expire. Riparian rights are usually included with the selling of the land.

The doctrine of prior appropriation asserts "first in time-first in right." The first person to divert water and put it to beneficial use has priority over those who come later. These rights permit the user to divert a specific amount of water, at a certain location, and for a specified use. The right has a definite date of priority. Unlike riparian rights, appropriation right can be sold or transferred without regard for land title, lost through non-use, and long-term storage is permissible.

Generally speaking, the eastern states use the riparian doctrine and the western states are prior appropriation. The water rights and laws of Arkansas, Oklahoma, Texas, and New Mexico illustrate this range. See appendix A for a summary of each state's water rights. As one moves from the eastern United States westward, the climatic, topographic, and demographic conditions change (Figure 2). The eastern U.S. is more

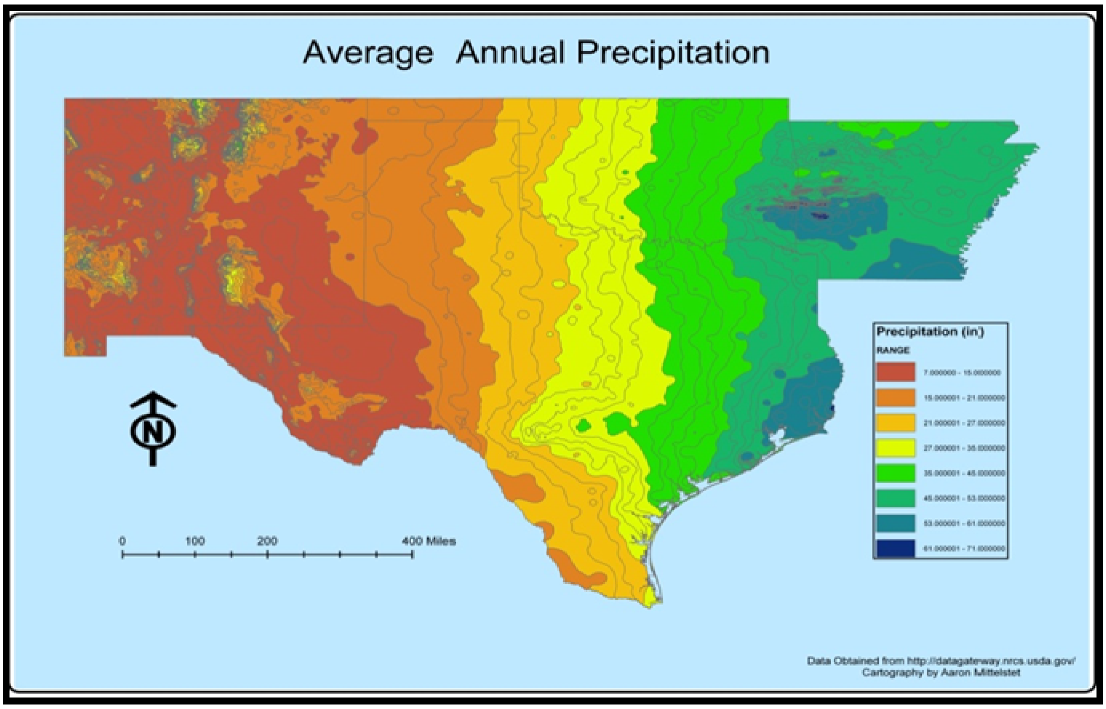

Figure 2. Map illustrating average annual precipitation from Arkansas to New Mexico

humid with a low evapotranspiration rate. Evapotranspiration is the loss of water from a watershed through evaporation and transpiration. Transpiration refers to the evaporation of water from plant leaves. As you move west, the climate becomes more arid with a higher rate of evapotranspiration. Arkansas, eastern Oklahoma and eastern Texas are humid, receiving an average of 30 to 60 inches of rain per year and therefore have more surface water. As you move into central and western Oklahoma and Texas and on into NewMexico, the climate becomes more arid, receiving an average of 12 to 20 inches or less of rain per year. With these changes in climate as you move from Arkansas westward to New Mexico, it is only fitting that the water laws in these states also change.

Diffused Surface Water

Diffused surface water is runoff before it enters a stream or lake. Once the water enters a stream, lake, or infiltrates the ground, surface or ground water regulations apply. The harvesting of diffused surface water is divided into two categories: land-based and roof-based. Land-based harvesting is water captured in an impoundment such as a pond or reservoir. Roof-based is capturing the rain from rooftops. In Arkansas, Oklahoma, Texas, and New Mexico, there are not any regulations preventing landowners from doing either one of these.

Land-based harvesting aids farmers in capturing rainfall, storing surplus water, aesthetics, and conserving other water resources. They can then use the stored water for irrigation, livestock, or household purposes.

Roof-based rainwater harvesting is considered a beneficial use and is promoted in each of the four states. This is different than some arid states where even roof-based water may be allocated to down stream users (Fitzgerald, 2008). It may be the only source of water supply for some rural areas and can help alleviate some of the strain placed on the public water supply systems in urban areas (Texas Rainwater Harvesting Evaluation Committee, 2006). The Texas Rainwater Harvesting Evaluation Committee (2006) calculated that with a collection efficiency of 80%, a rainwater harvesting system using 2,000 ft^2 of roof area will generate approximately 1,000 gallons of water for every inch of rainfall. In Texas they found that if rainfall was captured from 10% of the total roof area in the state, it would have little or no impact on stream flow. Arkansas, Oklahoma, Texas, and New Mexico allow roof-based harvesting and some residential areas in New Mexico require the installation of rainwater harvesting systems. For example in Santa Fe, rainwater harvesting systems are required on all new residential structures greater than 2,500 square feet (Texas Rainwater Harvesting Evaluation Committee, 2006).

Surface Water

Arkansas

The large number of streams and lakes in Arkansas contributes greatly to the way the people are permitted to use the water. Over 2% of Arkansas's total area is water or 1,107 square miles. See Figure 3 for comparison to Oklahoma, Texas, and New

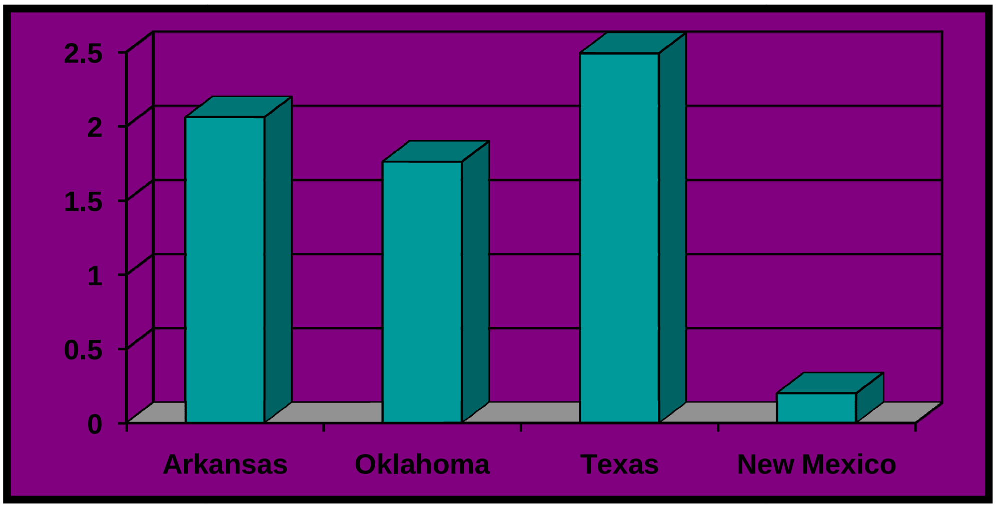

Figure 3. Comparison of States' total area that is surface water

Mexico (Statistical Abstract, 2007). The primary right to use water from streams or lakes is given to those whose land touches a river, stream, or lake. They are referred to as riparian landowners (ANRC Surface Water Rules Subtitle II §301.3, GG). These landowners may withdrawal a reasonable amount of water compared to other riparian landowners. "Reasonable use" is determined by comparing a given use with uses by other riparians (Looney, 1998). Whether or not a use is "reasonable" can only be determined after the use has commenced. This problem leads to uncertainty as other riparian landowners alter their diversions, new users enter the watershed, and as precipitation varies (Looney, 1998).

A riparian landowner who wishes to divert surface water must register with the Arkansas Natural Resources Commission (ANRC Surface Water Rules Subtitle II §302.1 A). The exception is if the landowner diverts less than one ac-ft (326,000 gallons) of water in any given year, diverts water from a privately owned reservoir, natural lake or pond, or uses diffused surface water (ANRC Surface Water Rules Subtitle II §302.2 A-C). These riparian rights may not be sold apart from the land. Failure to register is subject to penalty (ANRC Surface Water Rules Subtitle II §302.7).

If research data supports the existence of excess water (25% of the average annual yield from any watershed above that amount to satisfy all current uses (ANRC Surface Water Rules 301.3R), from a watershed, a non- riparian landowner may apply for a permit from the Director of the ANRC (ANRC Surface Water Rules §304.2, 304.4A). This includes either transferring water within a basin, an interbasin transfer, or between basins, an interbasin transfer. In calculating excess surface water, the ANRC projects existing riparian uses, instream flow requirements, and navigation requirements to the year 2030. These needs are subtracted from the average annual flow, and the mandated 25% is used to calculate the "excess." Using this procedure, Arkansas has over 10 million ac-ft of excess surface water: 725,000 in the Ouachita Basin; 1,100,000 in the Red River Basin; 1,700,000 in the White River Basin; 2,700,000 in the Arkansas River Basin; and 4,100,000 in the Delta Basin (Looney, 1989).

Most non-riparian permits are requested by either irrigators or gas and companies. Before a permit application will be considered, the applicant must show proof that he/she has leased or has received permission from the riparian landowner to form an easement. The Director will determine whether the proposed water is excess surface water and is intended for reasonable and beneficial use (ANRC Surface Water Rules Subtitle IV §304.2). The Director may grant the permit, but may place special conditions such as limiting the withdrawal of water to certain seasons or times (ANRC Surface Water Rules Subtitle IV§304.6). The non-riparian landowner may lose the permit if any condition of the permit is violated or if the water is not put to beneficial use within two years from the date of issuance (ANRC Surface Water Rules, Subtitle IV §304.10 304.12). The applicant for a permit has the right to protest the action of the Director in either quantity of water permitted or in permit denial (ANRC Surface Water Rules Subtitle IV§304.16). A permit renewal fee must be paid before October 1st each year and the Director will issue the permit for a fixed period not to exceed 50 years (ANRC Surface Water Rules Subtitle IV §304.4, 304.7).

The most important difference in the application process between an intrabasin and interbasin transfer is that an interbasin transfer requires the applicant to publish a notice and the ANRC to hold a hearing to determine if the water meets the conditions to be transferred (ANRC Surface Water Rules Subtitle V §305.4). Within 30 days following the hearing, the Director will grant or deny the application and if granted may place special conditions on the permit (ANRC Surface Water Rules Subtitle V §305.7). Permits for both intra and interbasin transfers may be sold unless the permit is for irrigation (ANRC Surface Water Rules Subtitle IV- V §304.10, 304.13, 305.13, 305.17). The permits for irrigation are required to install a flow meter device that measures the amount of water diverted (ANRC Surface Water Rules, Subtitle VI§304.4 D).

If an individual wishes to transfer water (except bottled water) from Arkansas to another state, he/she must apply for a separate permit. This process is similar to the intra and interbasin transfer except that the ANRC will within 120 days decide whether to grant or deny the permit based on the following: water availability in Arkansas and in the state to where it will be sold, the present and future water demands of water users in Arkansas, whether there are water shortages in Arkansas, whether the water to be transported could be transported to alleviate water shortages within Arkansas, and the demands placed upon the applicant's supply in the state of intended use (ANRC SurfaceWater Rules Subtitle VI §306.5). If the ANRC recommends the transfer of water, it will recommend a price to be paid to the state of Arkansas (ANRC Surface Water Rules Subtitle VI §306.6.A, B). The Arkansas General Assembly must then approve the permit (ANRC Surface Water Rules Subtitle VI §306.6.C).

Water shortages have not been much of a problem thus far in Arkansas; however, the ANRC has developed a system of allocation for when this situation arises in the future. The following uses of water are permitted without allocation: diversions of less than 1 ac-ft, tailwater, exclusively owned water, diffused surface water, captured water, or water for non-consumptive usage (ANRC Surface Water Rules Subtitle VII§307.2). When a water shortage occurs, domestic and municipal use, minimum stream flow, and federal reserved rights must first be met (ANRC Surface Water Rules Subtitle VII §307.3). Once these needs are met, there is an allocation hierarchy. The ANRC first gives priority to agriculture, followed by industry, hydropower, and recreation to those registered riparian landowners. Preference is then given to riparian landowners who are not registered but have used the water before, non-riparian intrabasin transfer, and then to riparian interbasin transfer. At the bottom of the list for allocations and the first ones that must decrease or cease diversions are out of state transfer and riparian landowners who have never used the water before (ANRC Surface Water Rules Subtitle VII § 307.4).

Oklahoma

Eastern Oklahoma usually receives enough rain and has an adequate supply of surface water, but western Oklahoma is more arid with less surface water. Therefore, it is no surprise that their system of allocating surface water is quite different from Arkansas. All of the surface water in Oklahoma is publicly owned. The Oklahoma Water Resources Board (OWRB) has divided the state into 49 stream systems to help establish the amount of water available to Oklahoma users (OWRB, 1995). When determining the amount of water available for appropriation from a stream, the OWRB considers the mean annual precipitation, run-off in the watershed above the point of diversion, the mean annual flow, stream gauge measurements, domestic uses, and all other existing appropriations and designated purposes of the stream system. The amount of water available for appropriation from a lake or reservoir is based on a 98% dependable yield for the reservoir for municipal and industrial use and an 80% dependable yield of the reservoir for irrigation (Okla. Admin. Code §785: 20-5-5a(1, 2)).

Before 1963 Oklahoma had a dual appropriation system. In 1963 the Oklahoma Legislature replaced the hybrid appropriation system with the doctrine of prior appropriation, which states that the first person to obtain a water right has seniority over all of those who follow. All individuals with stream water rights prior to 1963 were considered "vested" and were allowed to continue to use their appropriated amount (Okla. Stat. tit. 82 §105.1A).

Any individual, corporation, or agency who wishes to use surface water in Oklahoma must obtain a permit from the OWRB (Okla.Stat. tit. 82 §105.1A). The only exception is the riparian landowners who use water for domestic purposes (Okla. Stat. tit. 82 §105.9). Domestic use includes irrigation not to exceed three acres, watering of livestock up to the normal grazing capacity of the land, domestic animals, fire protection, and all household purposes (Okla. Stat. tit. 82 §105.9) Water for domestic use may be stored in an amount not to exceed two years' supply (Okla. Stat. tit. 82 §105.2).

There is no preference in the appropriation of surface water as long as the water is put to beneficial use and is not wasted or polluted (OWRB, 1995). When an individual applies for a surface water permit, the OWRB determines if there is water available, if it will be put to beneficial use, and if it will interfere with current users (Okla. Stat. tit. 82 §105.12A1-3). The date the OWRB receives the application is the priority date. (Okla. Admin. Code §785:20-3-7). The applicant must make public knowledge his/her intent to appropriate (Okla. Admin. Code §785:20-5-1). Anyone believing their interests may be affected by the proposed use of water may protest the issuance of the permit (Okla. Stat.

tit. 82, §105.11). If the permit is issued, the OWRB may include conditions to protect existing rights and uses and current stream flows. An application to transfer water out of a stream system will be considered after all needs are met within the stream system (Okla. Stat. tit. 82, §112 A-B)

The Board issues five types of permits for stream use: *regular*, which permits the individual to use water year-round; *seasonal* for specified periods of the year; *temporary* for up to three months; *term* for a specified number of years; and *provisional temporary* for up to 90 days. A provisional temporary permit is not renewable and does not require a hearing or approval by the OWRB (Okla. Stat. tit. 82 §105.1C-G). Once a permit is issued, the water must be put to use within two years and the authorized amount fully used within seven years and at least one year in seven thereafter. (Okla. Stat. tit. 82 §105.16). The OWRB has approximately 2,600 surface water permits on file allocating 2.6 million ac-ft/yr (OWRB, Oklahoma Water Facts).

When water shortages occur, domestic users have rights to the surface water first. The right to water then goes to permittees according to seniority (priority administration). For example as seen

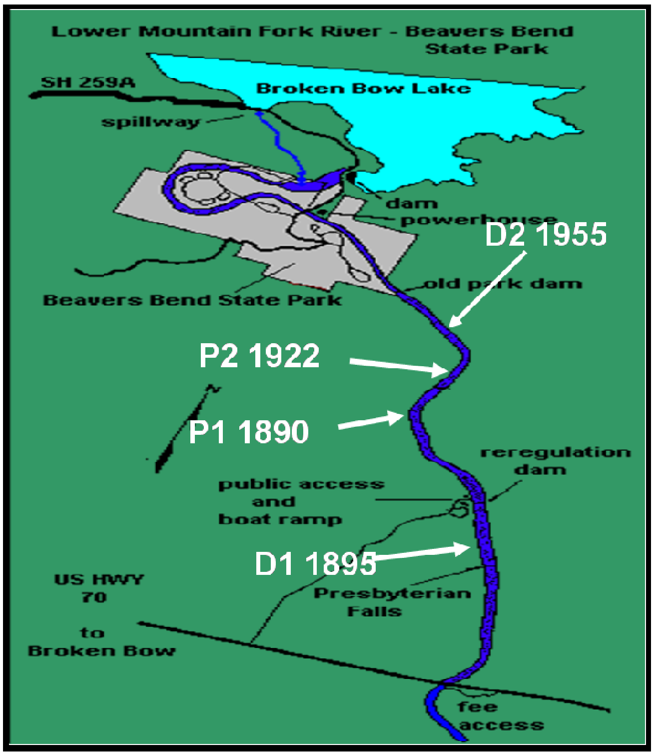

Figure 4. Example of priority administration in Oklahoma and Texas (http://www.okcoutdoornetwork.org)

in Figure 4, if there is not sufficient water for every water right holder in the basin, domestic users (D1 and D2) have priority over all other users. The water right holder with a priority date of 1890 (P1) has the next priority. Once those rights are met, P2 with the priority date of 1922 may then divert water.

Texas

Texas is similar to Oklahoma as far as being humid in the east and arid in the west. Texas has 15 major river basins and 196 major reservoirs (Water for Texas, 2007). Like Oklahoma, the surface water belongs to the state and may be appropriated, stored, or diverted for domestic, municipal, agricultural, industrial, or any other beneficial use (Texas Statures Water Code §11.021a-b; 11.023a-b). A permit is required from the Texas Commission on Environmental Quality (TCEQ) for the appropriation of surface water (Texas Statutes Water Code §11.021). Exceptions include diversion of water for domestic use or the construction of a dam or reservoir on one's private property with normal storage of 200 ac-ft. or less for domestic and livestock purposes, fish and wildlife, or commercial and noncommercial wildlife management For further details and exemptions see the Texas Water Code §11.142, 11.1421 and 11.1422.

Like Oklahoma, Texas has had different laws governing the use of surface waters often leading to conflicting claims over water rights. Therefore, in 1967 the Texas Legislature directed the predecessor agency to the TCEQ to settle the confusion over water right claims. Claimants had to prove when, where, and for what purpose they began to use the water. The state district courts looked over all claims and issued certificates of adjudication for approved claims. Each certificate was assigned a priority date based on when the water was first put to use (Rights to Surface Water in Texas, 2002). This priority date is important since Texas adopted the doctrine of prior appropriation (Texas Statutes Water Code §11.027). Texas courts have adjudicated most of the 10,000 claims (Rights to Surface Water in Texas, 2002).

For all new water rights, permits are issued by the TCEQ. The differences between certificates of adjudication and permits are that permits require no judicial review, but they may only be issued if there is unappropriated water available. If there is water available, a *regular* permit, where water may be withdrawn year round, or a *seasonal* permit, where water may only be withdrawn or diverted during certain times of the year, will be granted (Texas Statutes Water Code §11.135, 11.137). Unlike Oklahoma, Texas gives preference to domestic and municipal uses followed by agriculture and industry, mining, hydroelectric power, navigation, and finally recreation (Texas Statutes Water Code §11.024).

Unlike Oklahoma, there is not much unallocated water available in Texas; however, a term or temporary permit is available for water that is appropriated, but not currently being used. A *term* permit is granted to industries, mines, and agricultural enterprises for up to 10 years and may be renewed if the water-right holders are still not using all the water (Texas Statues Water Code §11.1381). *Temporary* permits are issued up to three years for road construction projects, mining, and irrigation (Texas Statues Water Code §11.1381). If the use of appropriated water is willfully abandoned for three consecutive years or is not used within 10 years, the water right will be forfeited and will become available for appropriation (Texas Statutes Water Code §11.030, 11.172).

An appropriator may obtain the right-of-way on private property in order to pump their water to where it is needed. If the party wanting the easement is not a corporation, district, city, or town, an application must be submitted to the TCEQ (Texas Statues Water Code §11.035c). A permit or an amendment to a current permit or certificate of adjudication is required to transfer water from one basin to another, an interbasin transfer (Texas Statutes Water Code §11.085a). Before granting the permit, the TCEQ holds a public meeting involving comments from the basin of origin and the basin receiving the water (Texas Statutes Water Code §11.085d). The applicant must publish the intent and if contested a hearing will take place (Texas Statutes Water Code §11.085e-g). Before 1997 it was not very difficult to obtain an interbasin transfer, but several amendments in 1997 made it more challenging to do so. One major change required existing water right holders whom amend their permit to allow interbasin transfer to lose their original priority date (Texas Statutes Water Code §11.085s). This makes interbasin transfer amendments junior to all other water rights, which is a big disadvantage during a water shortage (Schwartz, 2006)

The surface water permits allocate 20 million ac-ft yr^{-1} to water right holders, but during a drought only 13.3 million acre-feet is available (Water for Texas, 2007). Of this amount, only 9.0 million acre-feet can be used due to physical and legal constrains. Existing surface water supplies are projected to decrease to 8.4 million ac-ft by 2060, partly due to sediment accumulation in reservoirs (Water for Texas, 2007). Therefore water shortages are only expected to become more frequent in the future.

When there is a water shortage, water for domestic use receives first priority followed by senior water right holders (Texas Statutes Water Code §11.027). Priority administration (Figure 4) may work on the honor system as it does in Oklahoma or a watermaster may be appointed. Under the honor system, it is assumed that each individual will follow the rules of their water rights and cooperate with other permit owners in the basin. This system is inexpensive, but not everyone follows the rules. If it is believed that someone is taking more than their fair share or diverting water before a senior water right holder receives his or her water, the TCEQ may appoint a watermaster. One watermaster may be appointed for each water division (Texas Statutes Water Code §11.326). Water divisions, which are created by the TCEQ when necessary, administer adjudicated water rights. The commission of the TCEQ may divide the state into water divisions to secure the best protection of the water right holders (Texas Statutes Water Code §11.325). A watermaster monitors one or more river basins making sure that the domestic rights and those with seniority receive their water first. If someone diverts water that is not theirs, the watermaster has the authority to lock up the pumps. This allows some coordination of pumping when there is a shortage (Texas Statutes Water Code §11.327b). To help the watermaster determine the quantities of water diverted, the Commission may require any permittee to construct a measuring device (Texas Statutes Water Code §11.331).

New Mexico

New Mexico has very little surface water and therefore unlike the other states, it is appropriated strictly through prior appropriation. The surface water is declared to be public and subject to appropriation for beneficial use (New Mexico Water Code § 72-1-1). The surface water rights, established in New Mexico prior to 1907, have been recognized and confirmed by the state constitution. The date the water was put to beneficial use is the priority date (New Mexico Water Code § 72-1-2).

The Water Rights Division, with district offices in Albuquerque, Roswell, Deming, Las Cruces, Aztec, and Santa Fe administers both surface and ground water rights throughout the state (Annual Report 2005, 2006). Most of the surface water in New Mexico has been fully appropriated and in many parts of the State, the surface water has been fully appropriated since the early to middle 1900's. Even during periods of average water supply, demand in many parts of the State exceeds supply if all water rights and permits were fully exercised (New Mexico State Water Plan, 2003). New Mexico is currently in the process of adjudicating all water rights in the state to determine who owns what water rights, both surface and ground water, and in what quantity. Although only 20% of all water rights had been adjudicated as of 2008, 50% are in progress (Adjudications, New Mexico Office of the State Engineer).

To use water that is not appropriated, a permit must be obtained from the State Engineer (New Mexico Water Code § 72-5-1). Since the priority date is so important, an individual may first file a notice of intent to establish the priority date. The application must then be filed within one year. A notice of intention must include the purpose, amount, point of diversion, place of use, method of conveyance, and water use schedule (New Mexico Water Code § 72-5-1). The State Engineer determines if there is water available. If there is no water available, the notice of intention will be rejected (New Mexico Water Code § 72-5-7)

If no notice of intent was filed, the date the application is filed establishes the priority date. The application must contain the same information as the notice of intent. The State Engineer then determines if there is unappropriated surface water available and that the appropriation will not affect any current water right holders. If these conditions are not met, the application will be rejected. If there is water available, the applicant must then make the proposal to divert surface water public (New Mexico Water Code § 72-5-4). Any protest must be filed within 10 days of the last publication (New Mexico Water Code § 72-5-5). If the applicant and protestant cannot reach agreement, it may go to a hearing at which time the State Engineer will approve or deny the permit (New Mexico Water Code § 72-5-6).

The date of priority is very important in times of water shortages. When there is not enough water to go around, the senior water holders have priority over the junior water holders. In New Mexico, Native Americans, acequias (community ditches recognized by state law as political subdivisions of the state), and agricultural water users typically have seniority while municipalities and industrial, residential, and recreational users are typically junior water right holders (Priority Administration, Office of the State Engineer). Currently priority administration, the temporary curtailment of junior water rights, is only fully implemented on the Cimarron River and on Costilla Creek in northeastern New Mexico. Throughout the rest of the state, voluntary agreements are encouraged by the State Engineer. Some of these include shortage sharing, rotation, and water banking (temporary re-allocation of water among voluntary water bank participants without the need for a formal water right transfer or change of ownership) (Frequently Asked Questions, New Mexico Office of the State Engineer).

Eminent domain may be used to gain access to private land to transfer water from its source to its destination (New Mexico Water Code §72-1-5). When a permittee wishes to change the use of the water, point of diversion or anything else, a separate application must be filed, but the priority date remains the same. An individual may also sell the title to a permit or lease it for a period not to exceed 10 years unless it is to a municipality in which it may be leased for up to 40 years (New Mexico Water Code § 72-6-3). A permit may be canceled if all conditions are not followed (Surface Water Administration §19-26, 2.13). If the water is not put to beneficial use for four consecutive years, the State Engineer will send out a notice. If after one year, the water still has not been put to use, the permit will be forfeited (New Mexico Water Code § 72-5-28). The water will then be available for appropriation.

With the recent drought years, the State Engineer realized that they do not have the tools to conduct priority administration. Therefore, in 2004 the State Engineer launched the Active Water Resource Management (AWRM) initiative (Active Water Resource Management 19.25.13.5). The tools for AWRM include the following: creation of water districts, district specific rules and regulations, appointment of water masters, and measuring and metering. Water master districts may be formed wherever the state engineer deems it necessary for the economical and satisfactory administration of both surface and ground water (Active Water Resource Management 19.2512.12.A-D). The State Engineer will then adopt rules and regulations specific to the water master district (Active Water Resource Management 19.25.13.10). Water masters are in charge of the diversions and distribution of water in the water master district (Active Water Resource Management 19.25.13.7.EE). To help the water master administer water rights, the state engineer can require a meter to be placed on any diversion within a water master district and the water master may enter private or public land to perform the duties as are required to accomplish administration (Active Water Resource Management 19.25.13.20, 19.25.13.25). AWRM is first being developed in seven high priority basins (Figure 5).

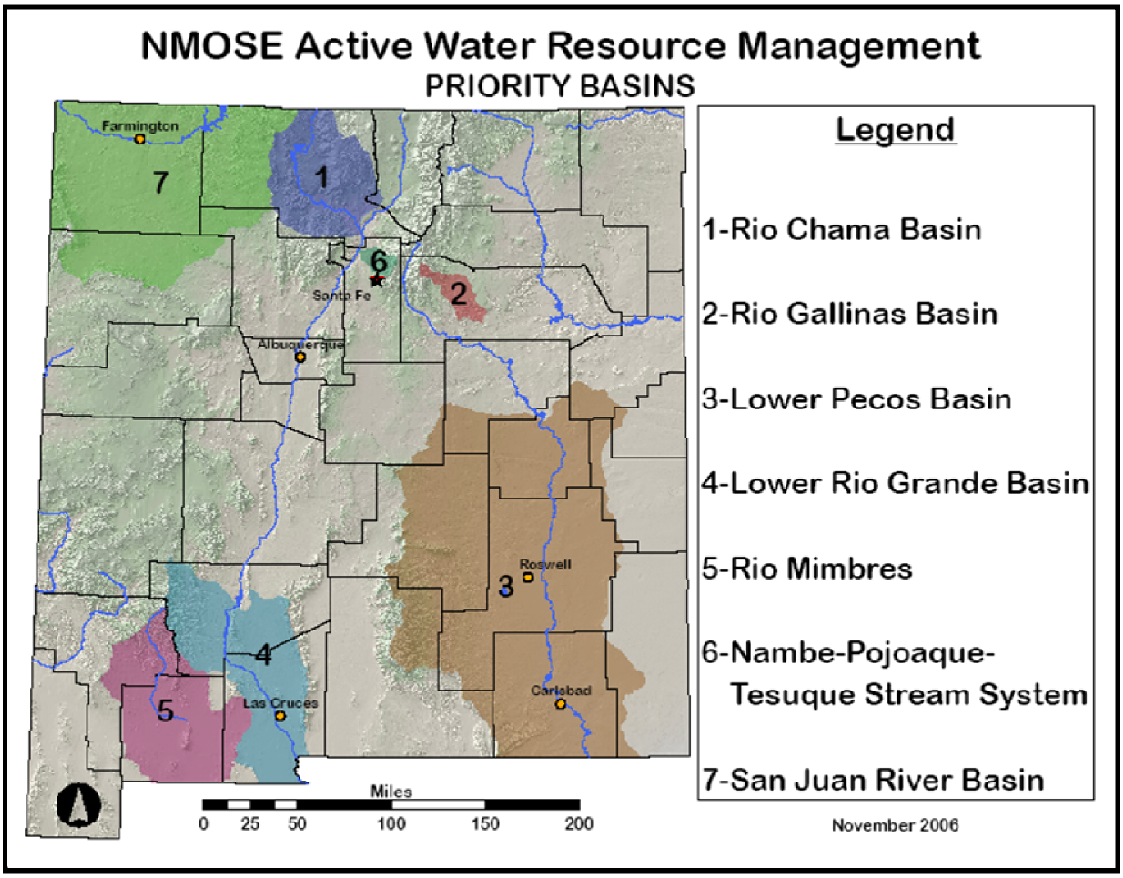

Figure 5. New Mexico's seven priority basins where Active Water Resource Management (AWRM) will first be implemented

Interstate Stream Compacts

Interstate stream compacts are intended to resolve and prevent disputes over waters shared with neighboring states and to assure the receipt of adequate surface flows and releases from upstream states. Each compact clearly spells out the quantity ofwater that a state may store or develop on an interstate stream. These compacts also deal with water quality and pollution problems (Interstate Stream Compacts, OWRB). Arkansas, Oklahoma, Texas, and New Mexico are involved in a total of 12 interstate compacts (Table 1).

Table 1. Interstate Stream Compacts

Compact	States Involved
Arkansas River	Arkansas, Oklahoma
Red River	Arkansas, Oklahoma, Texas, Louisiana
Arkansas River	Oklahoma, Kansas
Canadian River	Oklahoma, Texas, New Mexico
Pecos River	Texas, New Mexico
Rio Grande	Texas, New Mexico, Colorado
Sabine River	Texas, Louisiana
Colorado River	New Mexico, California, Colorado, Nevada, Utah, Wyoming, Arizona
Upper Colorado River	New Mexico, Colorado, Utah, Wyoming, Arizona
La Plata River	New Mexico, Colorado
Costilla Creek	New Mexico, Colorado
Animas-La Plata Project Compact	New Mexico, Colorado

Sources: Interstate Stream Compacts, OWRB; Compacts, New Mexico Office of the State Engineer; Texas Statutes Water Code, Title 3 River Compacts.

Ground Water

Arkansas

Although Arkansas has a lot of surface water, 63% of the water used comes from the ground. From 1985 to 2004, the amount of ground water pumped increased 70% to 6495 million gallons per day. Ninety-five percent of the ground water comes from the Mississippi River Valley alluvial aquifer (ANRC, 2007). For the 2005 water year, there were almost 55,000 registered wells reported and 98% were for agriculture (ANRC, 2006). Most of these wells were for irrigation in the eastern part of the state.

Like surface water, Arkansas landowners may withdraw ground water from underlying aquifers based on “reasonable use”. This right is not severable from the land title, and the right to extract and use ground water cannot be sold separate from the land. Use of water for domestic purposes or those with a maximum flow rate of less than

50,000 gallons per day do not have to be registered (ANRC, 2005). All other ground water use must be registered. As long as the water is put to beneficial use, property owners may withdraw all of the water needed. Arkansas Code Annotated § 15.22-915, passed in 2001 mandates that any well withdrawing ground water from a sustaining aquifer must have a properly functioning metering device. These aquifers include the Sparta, Memphis, Cockfield, Cane River, Carrizo, Wilcox, Nacatoch, Roubidoux and Gunter. Domestic wells are exempt.

In some areas the ground water is being withdrawn much faster than it can be recharged. If this trend continues, it may result in damage to the aquifers and a serious ground water shortage (ANRC Critical Groundwater Designation). If an aquifer is affected by over pumping, the ANRC may list it as critical (ANRC, 2005). Although two aquifers have been designated critical, they are not yet regulated. However, there are tax incentives for those who install water conservation practices (ANRC Critical Groundwater Designation). The Water Resource Conservation and Development Incentives Act encourages water users to invest in the construction of impoundments to use available surface water, to convert from ground water to surface water use, and to level land to reduce the quantity of water needed to irrigate agriculture (ANRC Tax Incentives). If these measures are not successful in the near future, the State will have to consider regulatory alternatives to preserve the aquifers at a sustaining level (ANRC, 2007).

The ANRC produces *The Ground Water Protection and Management Report* annually providing a summary of ground water protection and conservation programs administered by the ANRC (ANRC, 2007). It shows that water levels are dropping. A

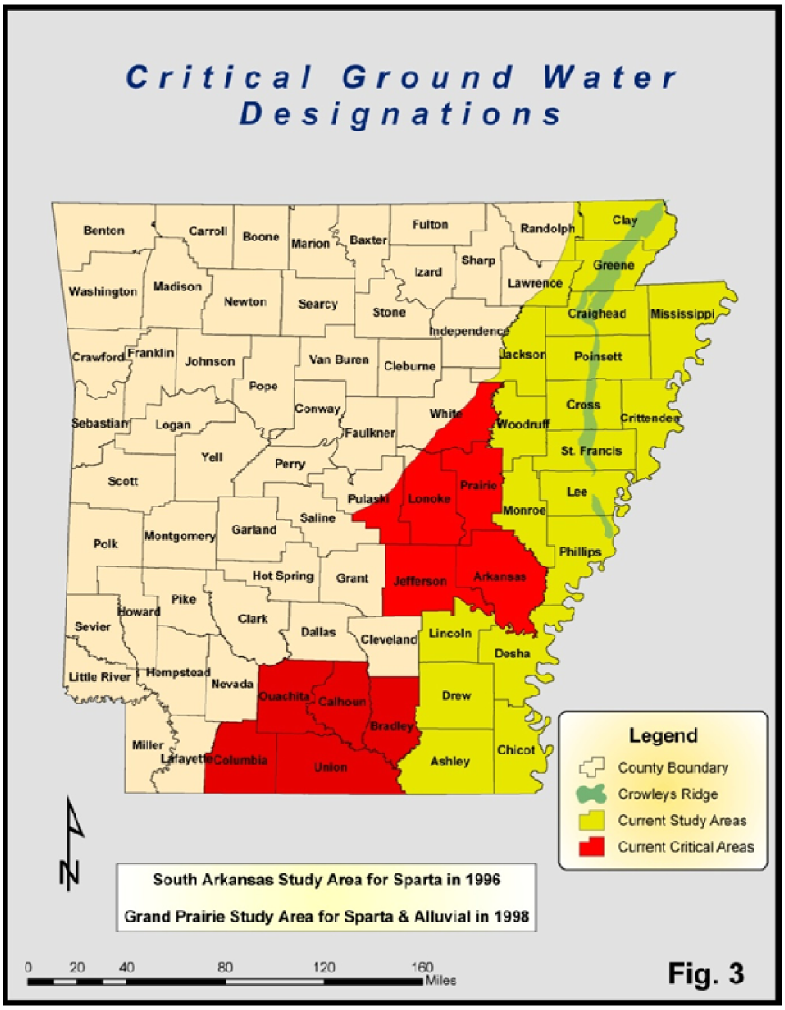

Figure 6. Map of the critical groundwater designations in Arkansas

five-county area of the Sparta Aquifer in Southern Arkansas and the alluvial and Sparta/Memphis aquifers in the Grand Praire Area in eastern Arkansas were designated critical regions in 1996 and 1998 respectively (Figure 6). Through education and conservation practices, the declining of the Sparta Aquifer has slowed. The Grand Praire Area however, continues to decline rapidly. The Cache Study Area, though not yet designated as a critical region, has also showed significant declines in water level (ANRC, 2007).

Oklahoma

Ground water is an important source of water in Oklahoma and is considered private property. In 2000, 44% of the total 1,172 million gallons of freshwater withdrawals came from the ground. Three-fourths of this was for irrigation (Tortorelli, 2000). Eighty percent of all ground water withdrawals take place in western Oklahoma. The majority of this is pumped from the Ogallala in the High Plains Region for irrigation.

The current groundwater law, passed in 1972, allows landowners or lessees to obtain a permit from the OWRB to use ground water based on the number of acres of the applicant's land that overlies a ground water basin. A permit is not required for domestic use (Okla. Stat. tit.82 §1020.7). The 1972 law determined that those individuals that already had water rights were allowed to continue to use their previously authorized amounts. Where studies have not been done to determine the amount of water in a ground water basin, temporary permits are given. Approximately half of the ground water permitted comes from aquifers which have not yet been studied or there is insufficient data. These permits allow the individual to withdraw two ac-ft of water for each acre of land owned or leased by the applicant. If studies have been done in the area, the permittee is usually allowed slightly more or less depending on the amount that may be safely withdrawn. This is based on a minimum basin life of 20 years (Okla. Stat. 82 §1020.11(B)). As of 2008, hydrogeologic studies have been completed on five major bedrock aquifers and ten major alluvial and terrace formations (Figure 7) (OWRB, Ground Water Studies)

A landowner or lessee may file an application for one of four ground water permits. If a hydrologic study has been done in the area, a *regular* permit may be issued (Okla. Stat. tit. 82 §1020.11A). If no study has been conducted, a *temporary* permit may be issued. To obtain either a regular or temporary permit, an application must be submitted to the OWRB and the intent published (Okla. Admin.Code § 785:30-3-1, 4).

At the hearing the intent to withdraw water may be protested (Okla. Admin.Code §

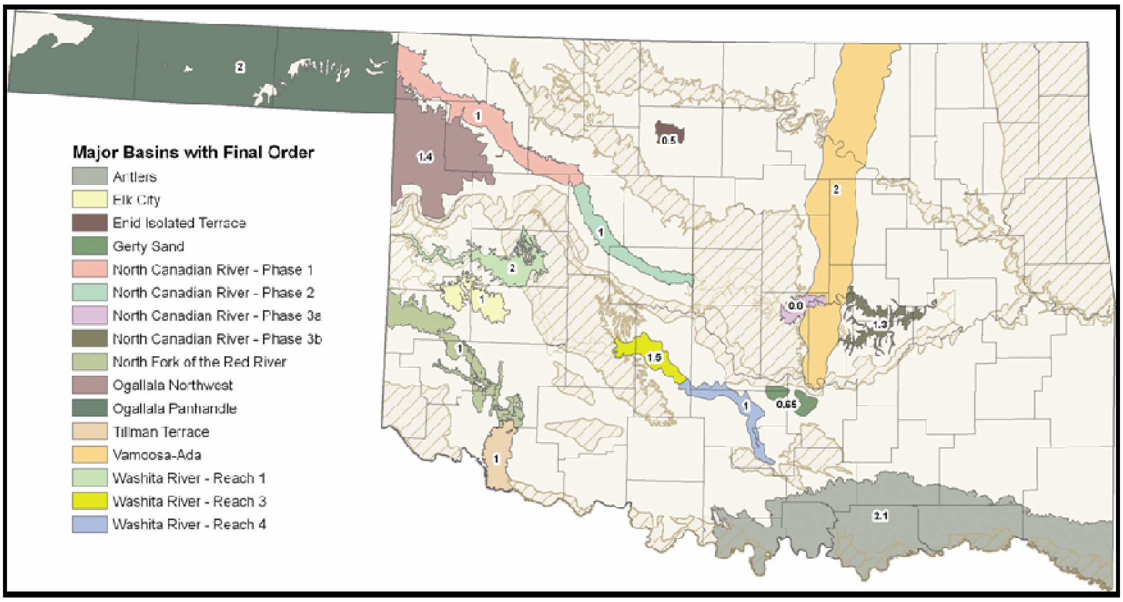

Figure 7. Map illustrating the major aquifers in Oklahoma where final order has been ordered

785:30-3-4) and the OWRB must determine that the applicant owns or leases the land, the land overlies a fresh groundwater basin or subbasin, the proposed use is beneficial, and there will not be any wasting or pollution of the water. Once this is all completed, a permit may be issued (Okla. Admin Code § 785:30-3-5). Each year a temporary permit must be revalidated and it may be protested (Okla. Admin Code §785:30-5-2).

There are also *special* and *provisional temporary* permits. A special permit may be issued for up to six months and renewed up to three times. It permits the withdrawal of more water than a regular or temporary permit (Okla. Stat. tit. 82 §1020.11)). Provisional temporary permits, often sought by oil companies, are issued for up to 60 days. A public hearing is not needed for a provisional permit, but need only to be approved by the director of the OWRB (Okla. Stat. tit. 82 §1020.10).

A ground water permit may not be lost due to nonuse, but may be canceled for failure to report annual usage or suspended for wasting the water (Okla. Stat. tit. 82 §1020.15). A meter is not required on Oklahoma wells, but if the majority of landowners in a basin desire a meter to be put on a well, the OWRB must comply (Okla. Admin. Code 785:30-13-3).

Texas

Texas' population is growing at a rapid rate and therefore more and more water is going to municipalities and industries. The Texas Water Development Board projects that by the 2040's more water will be used by cities and industry than by agriculture (Texas Cooperative Extension). Fifty-nine percent of the water used in the state comes from the 9 major and 21 minor aquifers. Unlike surface water, which is state-owned, the right to use ground water belongs to the owner of the land. Throughout much of the state, no permit is required and one may withdraw as much water as needed and for any reason (Texas Water Law). This is called the rule of capture and has been in place since 1904. Basically the deepest wells and biggest pumps get the water as the shallower wells go dry (*Houston & T.C. Ry. Co. v. East, 1904*).

Current Texas Supreme Court rulings stand by this rule (*Sipriano v. Great Spring Waters of America, et al, 1999),* but courts have imposed a few judicial limitations on the rule of capture. Water must not be wasted, pumped just to harm a nearby neighbor, or pumped from a slant-drilled well that crosses someone else's property (Texas Cooperative Extension).

The Texas Legislature has passed a few laws to restrict unlimited ground water pumping from the underflow of a river, from the Edwards Aquifer within the jurisdiction of the Edwards Aquifer Authority from an aquifer and within the jurisdiction of a ground water conservation district (GCD) (Texas Cooperative Extension).

GCD's are the state's preferred method of managing ground water (Texas Water Code §36.0015). The first GCD was formed in 1951 and the Texas Legislature has encouraged the forming of others. As of December 2007, 97 GCD's (Figure 8) have

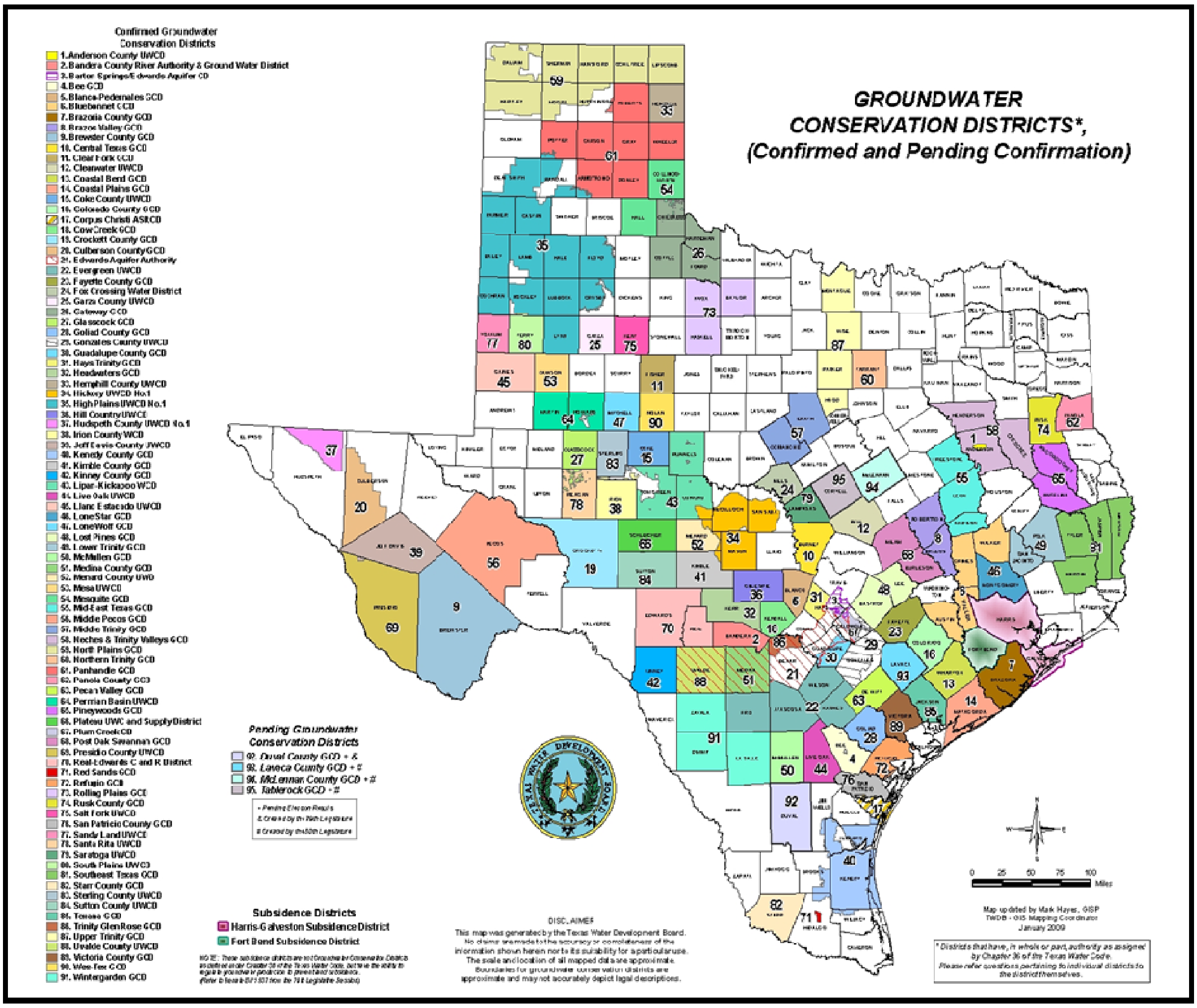

Figure 8. Map illustrating the Groundwater Conservation Districts (GCD's) in Texas

been created in the state (TCEQ, TWDB, 2007). Their purpose is to develop and implement management plans to conserve and protect ground water resources (Texas Water Code §35.0015).

Each GCD must develop and submit a management plan to the Texas Water Development Board (TWDB) within three years of being formed (Texas Water Code §35.1072a). Each plan must address the following management goals, as applicable: (1) providing the most efficient use of ground water; (2) controlling and preventing waste of ground water; (3) controlling and preventing subsidence; (4) addressing conjunctive surface water management issues; (5) addressing natural resource issues; (6) addressing drought conditions; (7) addressing conservation, recharge enhancement, rainwater harvesting, precipitation enhancement; and (8) addressing the desired future conditions of the ground water resources (Texas Water Code §35.107a). Once a management plan is submitted by the TWDB, it must be approved. At least once every five years, each GCD must review and resubmit their management plan with or without any revisions (Texas Water Code §35.1072e).

Each GCD enforces its management plan through permitting and regulating well spacing and production (Texas Water Code §35.1071f). Each ground water user must obtain a permit to drill and operate a well, although some exceptions do apply (Texas Water Code §35.113a). These can be found in the Texas Water Code § 36.117. A district may regulate the spacing of water wells and the production of ground water in order to minimize the drawdown of the water table, to control subsidence, to prevent interference between wells, to prevent degradation of water quality, or to prevent waste (Texas Water Code §35.116a).

New Mexico

Since there is a small quantity of surface water in New Mexico, ground water is an invaluable resource. Approximately 90% of the people depend on this precious resource for drinking (New Mexico State Water Plan, 2003). With most of the surface water in the state being appropriated, most new water rights are for ground water. The Office of the State Engineer processes an average of 19,000 water right permits a year and the majority are for ground water. Approximately one-third of the ground water permit applications are for domestic use or stock uses (Annual Report, 2005-2006). Unlike Arkansas, Oklahoma, and Texas, all ground water in New Mexico is now publicly owned and therefore a permit is required to use it (State of New Mexico Statutes §72-12-18). Until recently, there were undeclared ground water basins that were not under jurisdiction of the State Engineer. This now makes all water, both surface and ground, in New Mexico subject to appropriations and is therefore administered and regulated by the State Engineer. There are four types of ground water permits available: regular, temporary, livestock, and domestic.

Much of the ground water in New Mexico is already appropriated. To obtain a *regular* ground water permit for unallocated water, the water must be put to beneficial use, not interfere with existing water right holders, and not adversely affect public welfare and conservation. New Mexico's water law recognizes the interaction between ground and surface water; therefore, the proposed ground water diversion must not interfere with surface water rights. If the proposed ground water appropriation is in stream-related basins, the applicant may purchase surface water rights to offset the amount of the proposed application.

An application must first be filed with the Office of the State Engineer stating the amount of water applied for, the location of the well, the name of the owner of the land, where and for what purpose the water will be used, and the place of diversion (State of New Mexico Statutes §72-12-3A). If the proposed well location is on private property, the applicant must obtain written permission from the landowner giving the applicant access to the land to drill and operate a well (State of New Mexico Statutes §72-12-3B). The date an application is filed is the priority date (Office of the State Engineer, 2006§1-2). If the State Engineer finds the application acceptable, a notice of intent must be published. Anyone who feels that the proposed appropriation will affect their water right must protest the application within 10 days of the last publication (State of New Mexico Statutes §72-12-3D). If the application is protested, a hearing will be held before the State Engineer (State of New Mexico Statutes §72-12-3 F). If the State Engineer finds that the proposed water right will not interfere with other water rights and will be put to beneficial use, a "Certificate and License to Appropriate" will be granted (State of New Mexico Statutes §72-12-3E). The State Engineer may place specific conditions on the permit to protect existing water right holders.

A *temporary* permit may be obtained for the following uses: prospecting, mining, construction of public works, construction of highways and roads, or drilling operations to discover or develop natural mineral resources. Up to three ac-ft of water for up to one year may be granted if it will not permanently impair existing water rights (Office of the State Engineer, 2006 §1-15.6). The application can be renewed and a permit may be granted in any year to the same applicant for each proposed use (Office of the State Engineer, 2006 §1-15.6.1, 3). The application will be denied if the appropriation will take 0.1 ac-ft or more from a fully appropriated stream (Office of the State Engineer, 2006 §1-15.6.4).

A separate permit is required for *livestock*. When a person or corporation applies for a livestock permit, it is always granted (State of New Mexico Statutes §72-12-1.2). Three ac-ft of water may be withdrawn yearly from each well. It is recommended that the wells be spaced at least 50 feet apart.

The fourth permit type and by far the most numerous are those for *domestic* use. Ninety percent of all residents in New Mexico depend on domestic wells. As of 2000, there were approximately 137,000 domestic wells (Office of the State Engineer, 2000). This was up from almost 112,000 in 1995. Of the 137,000 wells, over 36,000 were within one mile of perennial streams and over 37,000 were between one and five miles of perennial streams (Office of the State Engineer, 2000). With the large number of wells and the affect that they can have on other water rights, the Office of the State Engineer prepared new rules and regulations for domestic wells in the year 2006. The new rules and regulations do not affect existing domestic wells, from which three ac-ft yr^{-1} may be diverted.

Domestic use includes water for household purposes, irrigation of one acre or less, and drinking and sanitation purposes for governmental, commercial, or non-profit facilities (State of New Mexico Statures §72-12-1.1). To obtain a permit, an application must be filed with the State Engineer that includes the location and purpose of the well, the number of households to be served, and the landowner where the well is located (State of New Mexico Statutes §72-12-3). If the well is for a single household, up to one ac-ft per year may be pumped. The maximum amount that may be withdrawn from a well serving three or more households is three ac-ft yr^{-1} (Office of the State Engineer, 2006 §19.27.5.9 1, 2). Most domestic permits are granted although there are a few exceptions: the proposed well location has restrictions imposed by a court or it is in an area the government prohibits or does not recommend any new wells (Office of the State Engineer, 2006 §19.27.5.13-A). If the permit is approved, conditions may be included. A meter is required if the well is for multiple households, within a domestic well management area, imposed by a court, or for governmental, commercial, or non-profit facilities (Office of the State Engineer, 2006 §19.27.5.13-C).

An area may be declared a domestic well management area if the withdraw of ground water might affect existing surface water rights. Before an area may be declared a management area, the state engineer must hold a public meeting. Anyone who may be affected may then voice his opinion. In a domestic well management area, a single household may not withdraw more than 0.25 ac-ft yr^{-1} (Office of the State Engineer, 2006 §19.27.5.14 A, B, C). The State Engineer may cancel any permit where the person fails to comply with the conditions of the permit (Office of the State Engineer, 2006 §19.27.5.14). Domestic wells do receive a priority date and are subject to priority administration.

CHAPTER III

USING MODFLOW TO COMPARE MANAGEMENT ALTERNATIVES FOR A RIVER ALLUVIAL AQUIFER

Background

Ground water is a vital resource for the United States. In 2000, 26% of all water used came from the ground with the majority being used for irrigation followed by public water supply (Hutson, 2000). Though 74% of our water comes from lakes and rivers, depleting ground water can affect the baseflow in our rivers, which in turn will affect the quantity of surface water available. When a pumping well is located near a stream hydraulically connected to an unconfined aquifer, it intercepts ground water that normally would have discharged to the stream as baseflow. The baseflow of the stream is therefore reduced. If pumping continues, the hydraulic gradient may be reversed to where the stream will discharge only to the aquifer (Chen and Yin, 2001).

Models can be used to help us predict the effect that ground water pumping has on an aquifer and hydrologically connected surface water. The results of such a model can be used to help us make water policy decisions. For example, the New Mexico Office of the State Engineer has designated certain ground water flow models for guiding administrative decisions about drawdown effects (Balleau and Silver, 2005). Seventeen basins in the state have been modeled using MODFLOW (Balleau and Silver, 2005). Balleau and Silver (2005) developed a model using MODFLOW to study statewide well impacts in New Mexico. They consider simplified specifications to inform policy decisions concerning the effect of domestic wells on the state's aquifers and streams (Balleau and Silver, 2005).

Mukhopadhyay et al (1994) used the VTDN software to simulate ground water flow in an aquifer system in Kuwait. The system was modeled to evaluate four different possible future exploitation/development plans for the aquifer system under consideration (Mukhopadhyay et al. 1994). Pisinaras et al. (2007) used MODFLOW to study the effect of 87 irrigation wells on a semi-confined aquifer system in North Greece. They ran four management scenarios for 20 years to simulate the long-term aquifer response (Pisinaras et al, 2006). Rejani et al (2008) chose MODFLOW to analyze the aquifer response to various pumping strategies in India. They simulated five pumping scenarios to determine the best management strategy.

Though there have been several studies completed using ground water models to simulate various management scenarios, I am not aware of any that have utilized MODFLOW to compare the ground water policies between two states with one policy being based on a 20-yearr simulation that is not revisited and the other on a 50-year simulation that is revisited every five years. I chose to compare the ground water polices of Oklahoma and the Texas Groundwater Conservation District. The objective was to compare the pumping rates that each policy permitted and to simulate its effect on an alluvial aquifer system.

Sensitivity Analysis

Due to uncertainty with the model parameters, a sensitivity analysis can indicate which input parameters are most important in the simulations (Johnson, 2007). We chose to analyze the effect of hydraulic conductivity, specific yield, recharge, and streambed hydraulic conductivity on river leakage and aquifer storage. Hydraulic conductivity (K) can vary significantly based on the size, shape, and connectivity of pores and fractures in the aquifer (Haan et al. 1994). The K value of gravel can be as high as 10^3 m d^{-1} and clay can be as low as 10^{-7}m d^{-1}. It can vary greatly vertically and horizontally over short distances.

Specific yield (S_y), the amount of water that will drain from a saturated material due to gravity, can also vary significantly with sand having a specific yield of 22%, gravel 19%, and clay 2% (Haan et al. 1994). Specific yield and temporal changes in aquifer storage are conceptually well understood, but quantifying these components in the field from aquifer tests and applying these parameters to determine water availability is challenging (Gehman, 2009). For example, in a study done within the Denver Basin, the S_y calculated directly from core samples were found to be significantly lower than the S_y estimates derived from laboratory analysis and aquifer tests (Gehman, 2009; Woodward, 2002; Raynolds, 2004). This has resulted in underestimation of water level decline in the basin.

There are two sources of recharge (R) to an alluvial aquifer: precipitation and river leakage. While physical parameters of a model are considered static, ground water recharge rates from precipitation can be highly variable in space and time (Jyrkama, 2002). Precipitation can vary greatly from year to year, but when performing 20, 50, or even 100-year simulations, it is impossible to predict. For example, due to unexpected extreme drought years from 2001-2004 in the Colorado River Basin, the simulated outcomes of the Interim Surplus Guidelines (guidelines for regulating water supplies during high reservoir conditions) were inaccurate (Garrick et al, 2008).

Streambed conductivity (K_{sb}) can be one to three orders of magnitude lower than aquifer conductivity (Calver, 2001; Larkin and Sharp, 1992; Fox, 2007). There are various methods for calculating streambed conductance, but studies concluded that making multiple measurements at a stream location is more important than the accuracy of a single technique (Fox, 2007).

Water Laws

Each state appropriates its water resources differently. Some regulate surface and ground water separately, while others treat the two as one system. The managers of two water boards in the Burdekin River Delta in Australia, for example, concluded that the policies on surface and ground water need to be determined simultaneously (Hafi, 2003). The state of New Mexico’s water law recognizes the interaction between surface and ground water; therefore, a proposed ground water diversion must not interfere with current surface water rights (State of New Mexico Statutes). However, in Oklahoma and Texas the allocation of ground water is done without regard to its effects on surface water (Texas Water Code 35.003; Okla. Stat. 82:1020.9). Sole source aquifers such as the Edwards Aquifer in Texas and the Arbuckle-Simpson Aquifer in Oklahoma are exceptions (Edwards Aquifer Authority; 2008, Okla. Stat. 82:1020.9A-B1).

Oklahoma’s ground water law allows landowners or lessees to obtain a permit from the Oklahoma Water Resources Board (OWRB) to use ground water based on the number of acres of the applicant's land that overlies a ground water basin (Okla. Stat. 82:1020.9). Where studies have not been completed to determine the quantity of water in a ground water basin, temporary permits are issued (Okla. Stat. 82:1020.11B). These permits allow individuals to withdraw two acre-ft (2,466 m^3) of water for each acre (0.4047 ha) of land owned or leased by the applicant (Okla. Stat. 82:1020.11B). If a study has been conducted to determine the quantity of water available in the basin, the maximum amount that may be diverted is based on a minimum basin life of 20 years (Okla. Stat. 82:1020.9). The law requires that after a minimum of 20 years, 50% of the aquifer will retain some saturated thickness, or in other words half of the aquifer will be dry (Okla. Admin. Code 785:30-1-1). Dry by this definition is a minimum of 1.52 m of saturated thickness for alluvium and terrace aquifers and 4.57 m for bedrock aquifers (Okla. Admin. Code 785:30-1-1).

Throughout much of Texas, no permit is required to use the ground water, and one may withdraw as much water as needed for any reason. This is called the rule of capture and has been in place since 1904. Basically the deepest wells and biggest pumps get the water as shallower wells go dry (*Houston & T.C. Ry. Co. v. East, 1904*). However, the Texas Legislature passed a law to restrict unlimited ground water pumping from within the jurisdiction of a groundwater conservation district (GCD) (Texas Water Protection Committee, 2003). The Texas Panhandle Groundwater Conservation District adopted the 50/50 standard in order to have 50% of current supplies, or saturated thickness, still available in 50 years (Panhandle Groundwater Conservation District, 2005). Under this standard, the maximum pumping rate is then revisited every five years to see if the depletion rate needs to be adjusted (Panhandle Groundwater Conservation District, 2005).

Baseflow versus River Leakage

Under normal baseflow conditions, the aquifer loses water to the stream, but after significant pumping, the hydraulic gradient can be reversed to where the aquifer gains water from the stream. Chen and Yin (2001) looked at river leakage and baseflow reduction induced by ground water pumping in nearby aquifers. Baseflow is the discharge from the aquifer to the river and river leakage is the discharge from the river to the aquifer. They concluded that reduced baseflow has a longer term impact on streamflow than river leakage and that its impact can continue into the next pumping season (Chen and Yin, 2001).

Methods and Model Design

In this study the ground water policies of Oklahoma and the Panhandle GCD were compared using a model based on characteristics of the North Canadian River Alluvial Aquifer in northwest Oklahoma (Figure 9). The objective was to see which of the two ground water policies is more sustainable under increasing levels of aquifer development and to compare the effect that aquifer development has on baseflow and river leakage. I used MODFLOW's RIVER package, a product of the U.S. Geological Survey (Harbaugh and McDonald, 1996), to simulate the unconfined aquifer-stream system. MODFLOW uses the ground water flow equation to calculate the movement of water between cells. The equation for a homogenous, isotropic aquifer is

$$K\frac{\partial^2 h}{\partial x^2}+K\frac{\partial^2 h}{\partial y^2}+K\frac{\partial^2 h}{\partial z^2}=S_s\frac{\partial h}{\partial t}-R \qquad (1)$$

where K = hydraulic conductivity (L/T), x, y, and z are components of the hydraulic conductivity tensor, S_s = specific storage (dimensionless), R = inflow to the system (L/T), h = head, , and t = time (Anderson and Woessner, 1992). MODFLOW has advantages over analytical models because it takes into account the vertical flow component in the

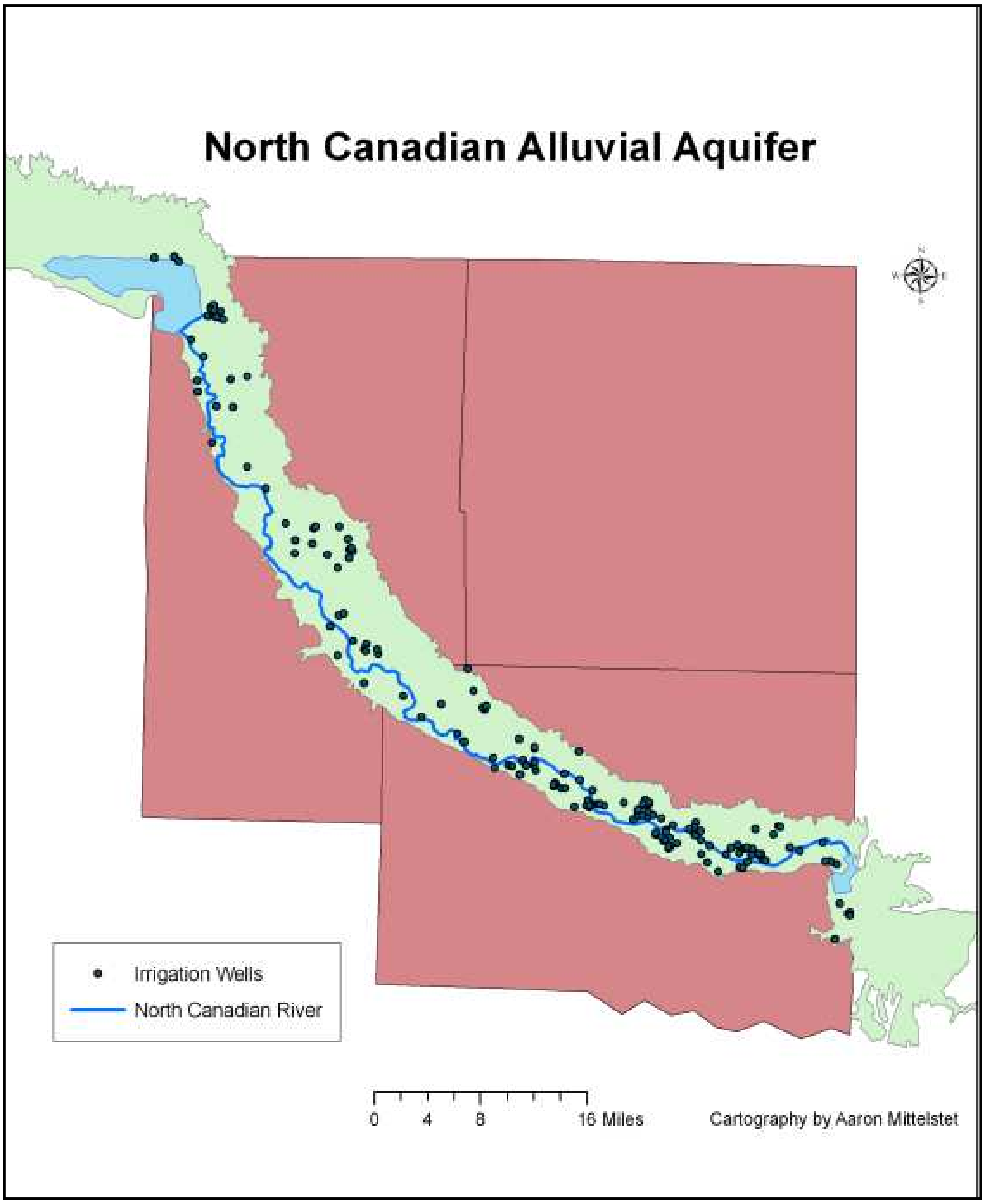

Figure 9. The North Canadian Alluvial Aquifer in northwest Oklahoma and its 150 irrigation wells. Canton Lake in the north and Lake Overholser in the south are connected by the North Canadian

vicinity of the streambed (Chen, 2001). MODFLOW's streambed conductance is

$$C = \frac{K_{sb} l W}{M} \tag{2}$$

where K_{sb} = streambed hydraulic conductivity, l and W = length and width of the stream in the finite difference cell, and M = depth of the streambed (Fox, 2007). MODFLOW calculates stream leakage as a product of C and the head gradient between the river and aquifer. The relationship between λ and C is given by (Fox, 2007):

$$\lambda = \frac{C}{l} = \frac{K_{sb} W}{M} \tag{3}$$

I used Processing Modflow Pro (Chiang, 2005) as an interface for model setup and simulations. Data from Christenson (1983) were used for model dimensions and parameters (Figure 10). The simplifications and assumptions of the model limit the accuracy of data obtained from its simulations. The aquifer domain is 100,000 m in length (the x-direction, or NW to SE in the North Canadian and 10,000 m wide (the y-direction). The model has one layer that is homogenous, isotropic and made up of 12,500 cells, with the east and west boundaries impermeable. The total depth is 20 m with a uniform 15 m originally saturated. Constant head boundaries were used to represent the two lakes, connected by a river. The river was modeled using the RIVER package, 10 m wide and 1.5 m deep. The RIVER package, which is used to calculate the flux of water between the stream and the aquifer, assumes that the stream stage remains constant throughout the simulation (Fox and Gordji, 2007). MODFLOW assumes the specific discharge through the streambed, q, is proportional to

$$q = \frac{K_{sb}}{M} s_w \tag{4}$$

Model of the North Canadian Alluvial Aquifer

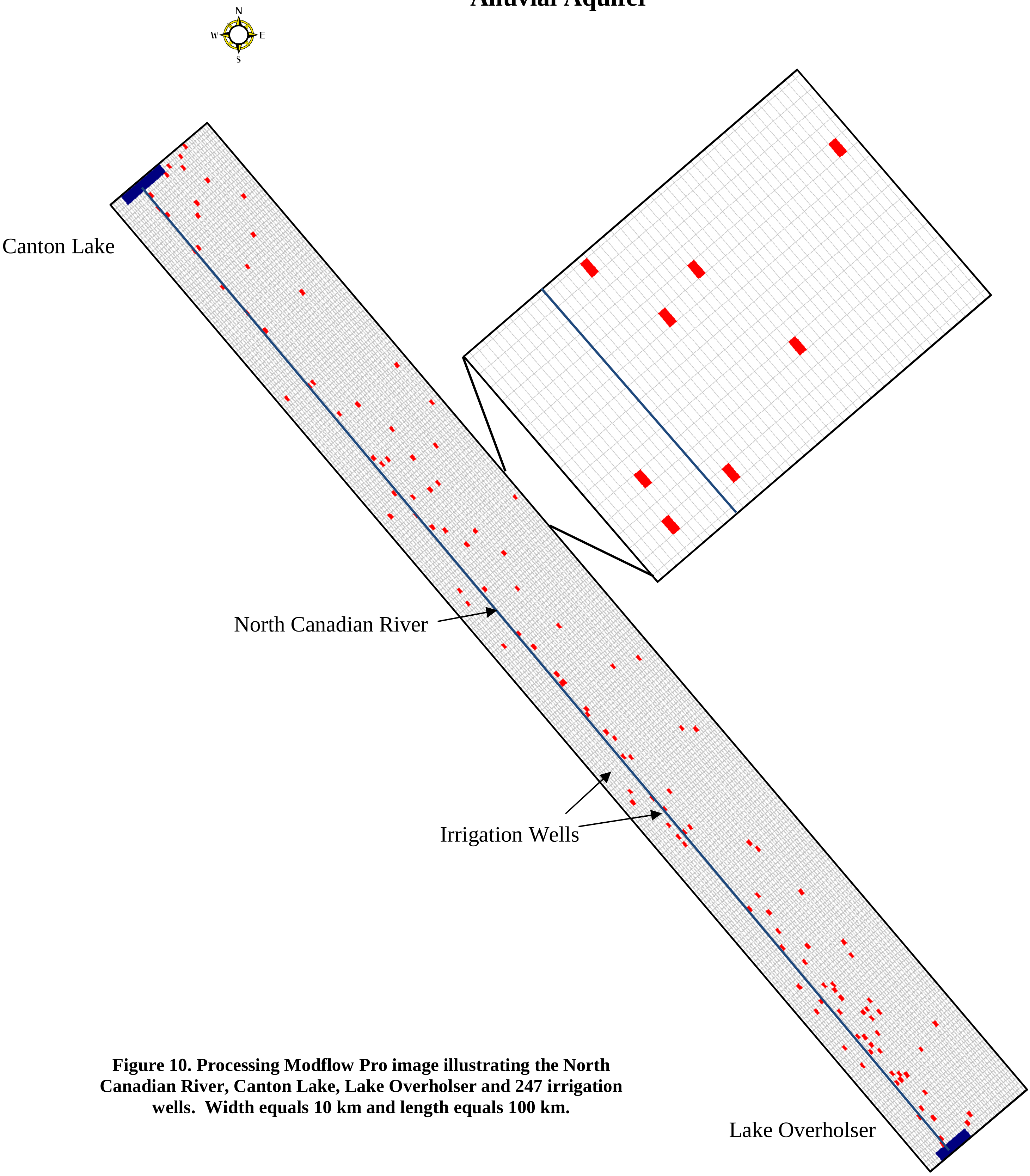

Figure 10. Processing Modflow Pro image illustrating the North Canadian River, Canton Lake, Lake Overholser and 247 irrigation wells. Width equals 10 km and length equals 100 km.

where q = specific discharge, K_{sb} = streambed hydraulic conductivity, M = streambed thickness, and s_w = drawdown defined as the difference between the hydraulic head in the stream and the hydraulic head in the aquifer (Fox and Gordji 2007). Equation (4) holds true for a fully saturated hydraulic connection between the stream and the aquifer; however, if the head in the aquifer drops below the streambed, MODFLOW's RIVER package assumes that seepage is no longer proportional to the aquifer head and becomes dependent on the water level in the stream and M

$$q = \frac{K_{sb}}{M}(H_w + M) \qquad (5)$$

where H_w=water level in the stream above the surface of the streambed (Zume and Tarhole, 2008; Fox and Fordji, 2007). Initially I set stream stage 0.5 m lower than the water table in the aquifer so the stream would gain water from the aquifer. The K was set to 30 m d^{-1} and K_{sb} to 3 m d^{-1} or 10% of the aquifer conductivity, with a thickness of streambed of 1.0 m. Based on Christenson's research (1983), I set S_y to 0.25 and R to 2.54 cm yr^{-1}.

Model Simulations

Sensitivity Analysis

A sensitivity analysis was performed using the model at 20% development, 494 wells, for 20 years. The objective was to evaluate the effect that K, S_y, K_{sb}, and R have on total storage and river leakage. See Table 2 for initial and varied parameter values.

Table 2. Initial and varied parameter values for sensitivity analysis

Parameter	Units	Minimum Value	Initial Value	Maximum Value
K	m d^{-1}	3	30	300
S_y	N/A	0.15	0.25	0.35
R	cm yr^{-1}	1.27	2.54	5.05
K_{sb}	m d^{-1}	0.3	3	30

A relative sensitivity coefficient was quantified for output y parameter relative to input parameter x (Heeren, et al., 2009):

$$S_r \frac{y}{x} = \frac{\frac{y - y_b}{y_b} * 100}{\frac{x - x_b}{x_b} * 100} \tag{6}$$

where $S_r(y/x)$ = relative sensitivity coefficient for output y relative to input parameter x, y = output under consideration, y_b = baseline value for output y, and x_b = baseline value for parameter x. Since K and K_{sb} vary significantly compared to S_y and R, I used the log of K and K_{sb} to make a better comparison with S_y and R. Therefore, total storage and stream leakage are y_1 and y_2 and K, S_y, K_{sb}, and R are the input parameters x.

Oklahoma/Texas

Oklahoma law specifies a maximum permitted withdrawal as the pumping rate where 50% of the cells go dry in 20 years. The model was run for 20 years with 2,433 time steps. One irrigation well was placed in every cell (12,500) in the model and I varied the pumping rate until approximately 6,250, or half of the cells went dry.

Once the allowable pumping value was determined, several simulations were completed at various stages of aquifer development. The objective was to simulate pumping when the aquifer was 10, 20, 30, 40, 50, 60, 70, and 80% developed. With the

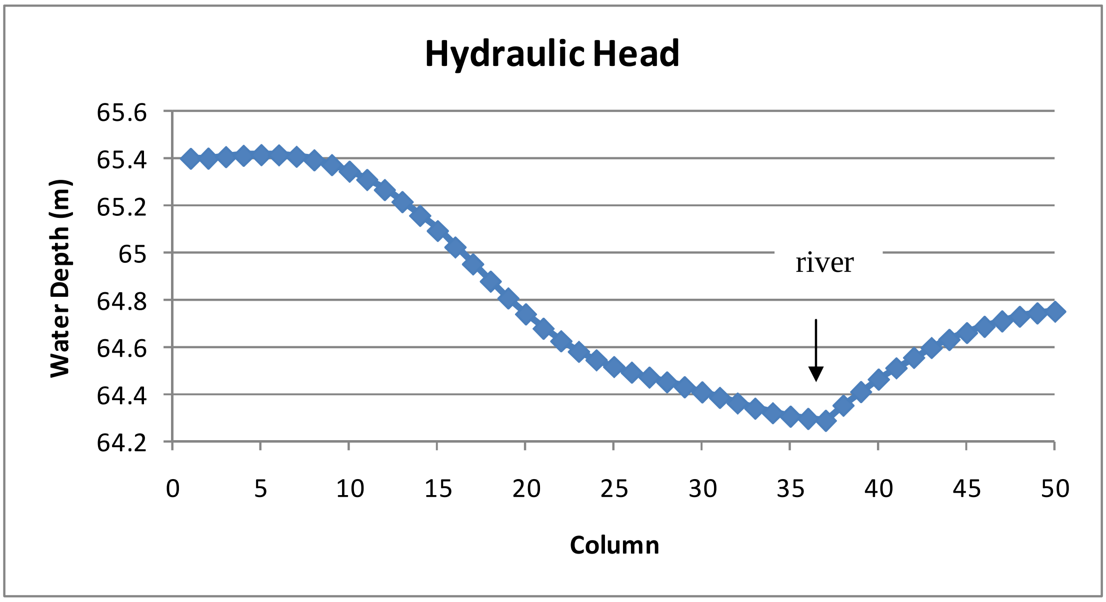

Figure 11. Graph showing the hydraulic head across the model after the 20-yr simulation at 10% development. Data taken from the middle of the model at row 125. The river has the lowest elevation head (see arrow).

total land area overlying the aquifer being 247,097 acres (99,600 ha), 10% aquifer development would be 247 wells. Each well represents 100 acres based on average pumping rate and number of acres irrigated per well in that part of the state (M. Kizer, personal communication, February 2009). Each simulation was run for 40 periods: 100 d pumping at 50 time steps followed by 265 d at 150 time steps. See Figure 11 for graph of the hydraulic head after simulation at 10% development and Figure 12Figure 13 for hydraulic head contour maps at the beginning and end of the simulation.

The simulations for Texas policy were run with the aquifer at 20, 40, 60, and 80% development. The difference was the pumping rate needed to be determined when the storage decreased by 50% in fifty years. Each simulation was run for 100 periods: 100 d pumping at 25 time steps followed by 265 d at 100 time steps.

Only irrigation wells were installed in the model since the majority of pumping is due to agriculture, and Zume and Tarhule (2008) found that overall the pattern of stream

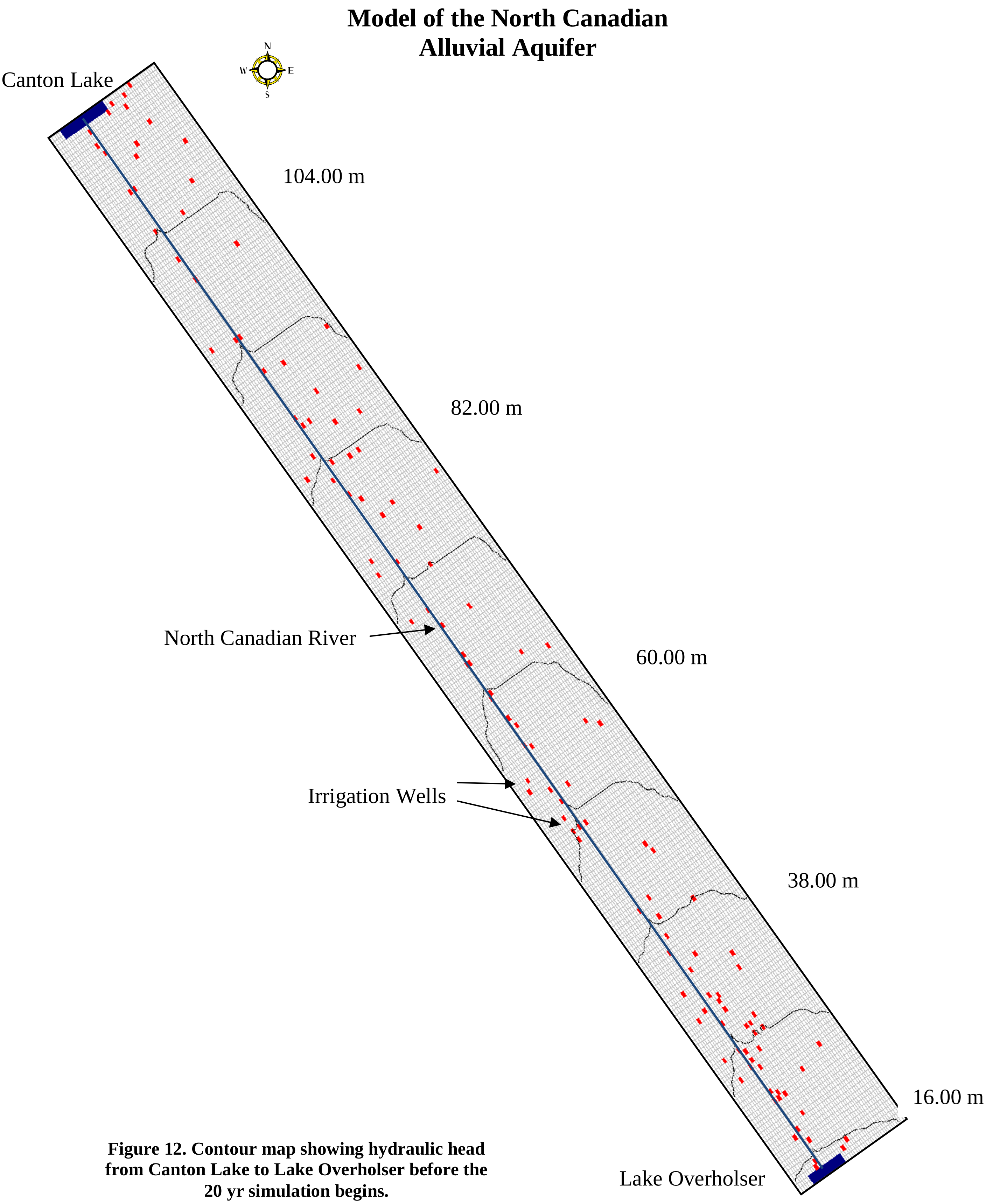

Figure 12. Contour map showing hydraulic head from Canton Lake to Lake Overholser before the 20 yr simulation begins.

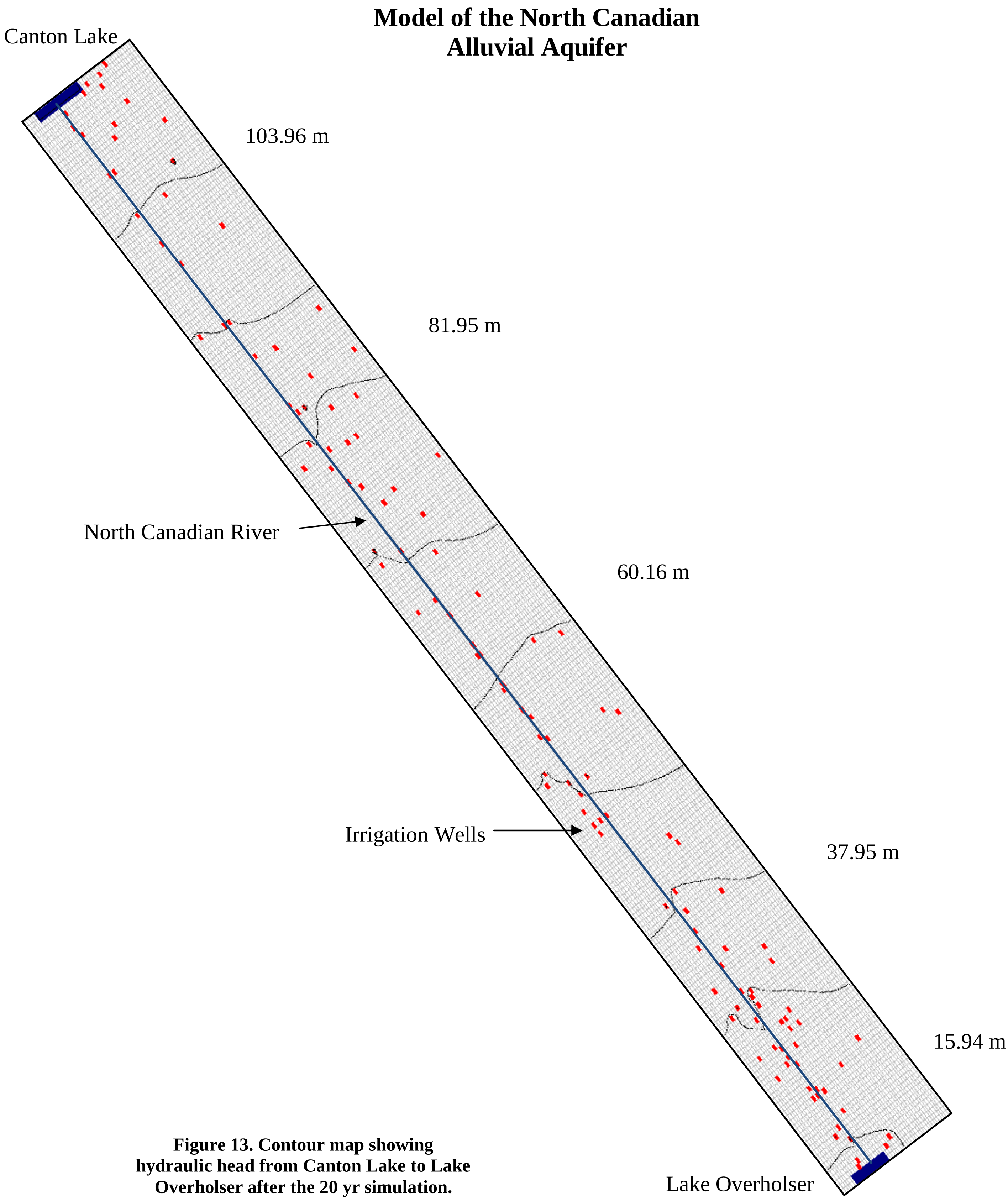

Figure 13. Contour map showing hydraulic head from Canton Lake to Lake Overholser after the 20 yr simulation.

depletion simulated by irrigation wells is similar to that obtained by pumping all wells within the aquifer. Data from the OWRB was used to place the first 150 wells at their true locations (OWRB). Using excel, wells were then added at randomly selected locations until the desired number of wells was reached. Each well was pumped 100 d followed by a 275-d non-pumping period.

Baseflow versus River Leakage

We analyzed baseflow and river leakage in the alluvial system at 10 and 20% aquifer development (247 and 494 pumping wells). Discharge was calculated at every time step in the MODFLOW simulation. The baseflow and river leakage were compared after each period (100 d pumping, 265 d no pumping).

Results and Discussions

Sensitivity Analysis

Recharge was the most sensitive parameter for total storage with a sensitivity coefficient of 0.0553 for both simulations compared to a K value of 0.0170 for 3 m d-1 and 0.0731 for 300 m d-1 (Table 3). The K had the greatest influence on river leakage with a sensitivity coefficient of 0.6872 and 1.3683, respectively.

These results were comparable to those of Christenson (1983) who tested variations in K, R, and K_{sb} over a 40-year simulation period with multiple pumping wells. Variations in K and R caused the computed heads to change significantly, while the computed heads were relatively insensitive to changes in K_{sb} (Christenson, 1983). Johnson (2007) analyzed the sensitivities of R, K, and vertical anisotropy and found recharge to be the most sensitive parameter followed by K. Johnson (2007) found very little sensitivity for the vertical anisotropy.

Table 3. Comparison of K, S_y, K_{sb}, and R sensitivity to aquifer storage and river leakage.

Parameter	Storage % Change	Sensitivity Coefficient	River Leakage % Change	Sensitivity Coefficient
K (m d-1)				
3	-1.13	0.0170	-44.80	0.6872
300	4.98	0.0731	98.84	1.3683
Sy				
0.15	2.47	-0.0620	23.55	- 0.5889
0.35	.02	0.0006	-16.12	-0.4031
K_{ab} (m d^{-1})				
0.3	-0.91	0.0044	-16.79	0.0801
30	.09	0.0005	2.55	0.0107
R (cm yr-1)				
1.27	-2.75	0.0553	29.48	-0.5088
5.08	5.74	0.0553	-39.63	-0.4152

Baseflow versus River Leakage

At 10% aquifer development (247 wells), the baseflow decreased to 38% after 5 years of pumping, 23% after 10 years, and 16% after 20 years. The river leakage decreased by 25% after 5 years of pumping, decreased by 8% overall after 10 years, and increased 18% overall after 20 years (Figure 14). The hydraulic gradient is reversed and the stream becomes a losing stream after approximately 9 years of pumping (see arrow).

These results were comparable to a similar aquifer in northwestern Oklahoma. Zume and Tarhule (2008) found that after pumping 131 irrigation wells for 1, 5, and 15 years, baseflow contributions to streams decreased to 47, 35, and 27% respectively and stream leakage increased to 35, 44, and 48%.

I found the changes were much more dramatic at 20% aquifer development with baseflow decreasing to 14%, 3%, and 2.5% after 5, 10, and 20 years of pumping. The river leakage increased 255% after 5 years of pumping, 483% after 10 years, and 692% after 20 years (Figure 15). After only 3 years of pumping the stream loses more water than it gains.

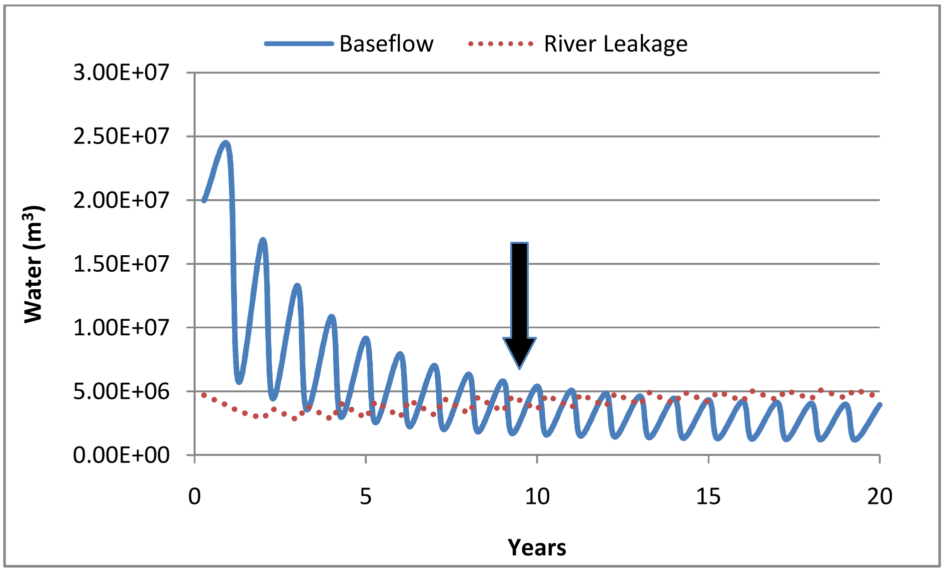

Figure 14. Total baseflow and river leakage after a 20-year simulation at 10% aquifer development. Arrow shows where hydraulic gradient is reversed.

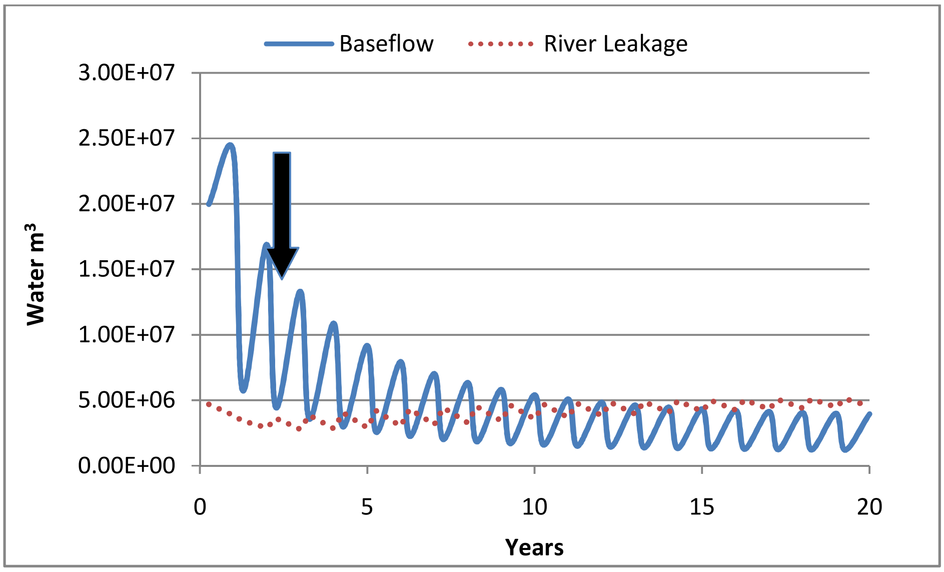

Figure 15. Total baseflow versus river leakage after a 20-year simulation at 20% aquifer development. Arrow shows where the hyraulic gradient is reversed.

Oklahoma/Texas Simulations

The amount of water that may be pumped from the alluvial aquifer so that 50% of the saturated thickness remains after 20 years of pumping was found to be 69 $m^3 d^{-1}$ or 1.03 acre-ft $ac^{-1} yr^{-1}$. With each irrigation well representing 40.47 ha (100 acres), the pumping rate for OK water law is 1270 $m^3 d^{-1}$ per well for 100 days. This pumping rate remains the same and need not be revisited. Therefore, as the population and quantity of agricultural land increases, more wells may be drilled into the aquifer, but each landowner will continue to be permitted 1.03 acre-ft of water for each acre of land owned or leased. This water policy works well if there is small demand for the water, but as the aquifer becomes more developed, the rate of water table decline and river leakage will continue to increase. For example, for the simulation at 10% development, average drawdown per cell after 20 years was 0.90 m, but the drawdown increased to 8.27 m at 80% development (Table 4)

For the Texas simulations at low development, the pumping rate was limited to 2.0 ac-ft $ac^{-1} yr^{-1}$ (2466 $m^3 d^{-1}$) because when more water was pumped from a single well, too many cells went dry. At 20 and 40% development, each individual could pump whatever they wanted (the rule of capture concept). At 60 and 80% development, each well would be limited to 1.14 ac ft $ac^{-1} yr^{-1}$ (1400 $m^3 d^{-1}$) and 0.50 ac ft $ac^{-1} yr^{-1}$ (615 $m^3 d^{-1}$) respectively to maintain the storage at 50% after 50 years of pumping. Though unlimited pumping is permitted at first, the permits are revisited every five years and the pumping rate readjusted to maintain 50% of total storage after 50 years.

Table 4.; Pumping rates and percentage of initial storage after various stages of aquifer development

Percentage of Aquifer Development	Oklahoma % of Initial Storage at 1.03 acre-ft	Pumping Rate in Texas (acre-ft/acre)	Texas % of Initial Storage
10	94	N/S	N/S
20	84	2.00	64
30	79	N/S	N/S
40	70	2.00	58
50	61	N/S	N/S
60	55	1.14	50
70	48	N/S	N/S
80	45	0.50	50

NS is not simulated

Conclusions

Ground water is an invaluble resource that each state regulates differently. The quantity of water and the policy that determines how it is to be allocated are both instrumental in maintaining the water level at a sustainable level for future generations. Calculating the quantity of water in a stream/aquifer system is challenging due to uncertainty and inhomogeneity. Sensitivity analysis showed that K and R are the most important parameters in modeling an alluvial aquifer, suggesting that money and efforts should focus on these parameters. Any reasonable estimate of K_{sb} and S_y should be adequate for analysis of interchange of water between the stream and alluvial ground water.

Though several states recognize the interaction between surface and ground water, Oklahoma and Texas do not. The current ground water law that Oklahoma has implemented allows efficient utilization of the aquifer with little decline of water table while development is low; however as the aquifer becomes more developed, the quantity of water that may be pumped per hectare of land owned or leased remains the same. This will cause a significant local drawdown of the water table, eventually depleting the resource. On the other hand, the rules of

Panhandle GCD permit unlimited pumping at first, but the depletion rate is revisited every five years and pump permits are revised such that the aquifer will never go dry.

This research demonstrates it is not only important to set a pumping rate based on the total storage in the aquifer, but it is important to consider interchange with the river (baseflow and recharge) and to retain flexibility to readjust permits if development exceeds the original assumptions. The North Canadian Alluvial Aquifer, on which this model was based on, currently has approximately 150 irrigation wells and is therefore about 6% developed. The model shows that as the number of wells increases, baseflow will decline and river leakage will increase. As the demand increases within the basin, the pumping rate should be revisited and readjusted accordingly.

CHAPTER IV

SUMMARY AND CONCLUSIONS

As seen from the water rights of Arkansas, Oklahoma, Texas, and New Mexico, the location and climate of a state indicates how they allocate their water resources and whether they have adopted the riparian, prior appropriation, or hybrid doctrine. In the future, each state will likely experience drought and water shortages due to urbanization and/or climate change. Each state has specific rules and regulations in place to deal with water shortages in the future. There are some tools that every state has available to them, others that are specific to their water allocation system, and other tools that are state-specific.

There are some tools such as water metering, conservation, and water reuse that can be effective in any region though they are not implemented in every state. Arkansas, for example, now requires metering on wells from all sustaining aquifers, New Mexico is requiring meters within water master districts, and Texas is starting to require them within groundwater conservation districts. Oklahoma, however, has not required any metering thus far. Conservation and water reuse, though not widespread, are becoming more popular especially in areas where there have been shortages in the past.

The appropriation doctrine has more flexibility and more tools than the riparian doctrine in times of water shortages. Some of these include permit administration, watermasters, water rotation, water sharing, and water banking. In theory, Oklahoma, Texas, and New Mexico all use priority administration in times of water shortages, yet only Texas and New Mexico have water masters to enforce it. At other times each state agency relies on other methods such as water sharing, banking, and rotation.

Each state has a hierarchy system of water allocation to implement in times of water shortage. Arkansas gives priority to domestic users and municipalities followed by registered riparian landowners. Oklahoma and Texas give priority to domestic users, but the right then goes to older water rights. The right to water during a shortage is based strictly on priority date in New Mexico.

Arkansas has designated areas as critical where over pumping has occurred and offers tax incentives to convert from ground to surface water. Unlike Arkansas, Oklahoma, and Texas, New Mexico will not permit ground water use if it will harm senior surface water right holders. New Mexico is also implementing the Active Water Resource Management Initiative (AWRM) within seven basins. Watermaster districts, watermasters, and metering will all be implemented within the basins to enforce priority administration. Texas now has a policy that makes it impractical to obtain a permit to transfer surface water outside its basin of origin.

Texas has different rules and regulation based on the ground water conservation district and Oklahoma allows varying amounts of water to be pumped based on whether or not the basin has been studied or not. In this study, MODFLOW was used to compare Oklahoma's and the Panhandle Groundwater Conservation District's ground water policies on management of a river alluvial ground water system. The simulations showed that in an aquifer with little development, Oklahoma's ground water policy can limit the decline of the water table, where the Panhandle GCD policy does not. However, as the aquifer becomes more developed, the Panhandle GCD policy would be more sustainable and the aquifer would not be permitted to go dry. If a water shortage occurs in the future and recharge to the aquifer decreases, Oklahoma's pumping rate can remain the same causing the aquifer and river to decline rapidly. On the contrary, the Panhandle GCD management plan is revisited every five years and therefore can be readjusted so that 50% of the aquifer storage remains in 50 years.

Each state has adopted a system of water allocation and rules and regulations based on tradition, population growth, and climate. When considering water policy changes, water managers should enquire how other states with similar characteristics are implementing their water polices. Based on what has worked and what has not, they can make the best decision based on their states water availability and future needs.

REFERENCES

Active Water Resource Management. Natural Resources and Wildlife, Administration and Use of Water-General Provisions. §19.25.

Adjudications, New Mexico Office of the State Engineer. Available at http://www.ose.state.nm.us/legal_ose_adjudications.html. Accessed 1 July 2008.

Anderson, M. P. and W. W. Woessner, 1992. *Applied Groundwater Modeling Solution of Flow and Advective Transport.* Academic Press, Inc. San Diego, California 92101

Annual Report, 2005-2006. New Mexico Office of the State Engineer/Interstate Stream Commission.

ANRC. 2005. Rules for the Protection and Management of Ground Water. Arkansas Natural Resource Commission. Title IV, Subtitle II.

ANRC. 2007. Arkansas Ground Water Protection and Management Report for 2006. Arkansas Natural Resources Commission.

ANRC Critical Ground Water Designation. Available at http://www.anrc.arkansas.gov/ANRC%20critical%20groundwater%20designation%20fact%20sheet.pdf. Accessed 2 January 2008.

ANRC Tax Incentives. Available at http://www.anrc.arkansas.gov/TaxIncentives.html. Accessed 5 January 2008.

ANRC Surface Water Rules. Title III. Rules for the Utilization of Surface Water, 2005.

Annual Report, 2005-2006. New Mexico Office of the State Engineer/Interstate Stream Commission.

Balleau, W.P. and S.E. Silver, 2005. Hydrology and administration of domestic wells in New Mexico. *Natural Resources Journal* 45: 807-847.

Calver, A. 2001. Riverbed permeabilities: Information from pooled data. *Ground Water* 39(4): 546-553.

Chen, X. 2002. Analysis of pumping-induced stream-aquifer interactions for gaining streams. *Journal of Hydrology* 275, 1-11.

Chen, X. and X. Chen, 2003. Sensitivity analysis and determination of streambed leakance and aquifer hydraulic properties. *Journal of Hydrology* 284: 270-284.

Chen, X, and Y. Yin, 2001. Streamflow depletion: modeling of reduced base flow and induced stream infiltration from seasonally pumped wells. *Journal of the American Water Resources Association* 37(1): 185-195.

Chiang, Wen-Hsing, 2005. 3D-Groundwater Modeling with PMWIN. Springer, Verlag Berlin Heidelberg.

Christenson, S.C., 1983. Numerical simulation of the alluvium and terrace aquifer along the North Canadian River from Canton Lake to Lake Overholser, Central Oklahoma. U.S. Geological Survey Water-Resources Investigations Report 83-4076.

Compacts, New Mexico Office of the State Engineer. Available at http://www.ose.state.nm.us/legal_compacts.html. Accessed 7 July 2008).

Edwards Aquifer Authority, 2008. Strategic Plan 2009-2011

Fitzgerald, Dan. Who Owns the Rain That Falls on Your Roof? Colorado Central Magazine. May 2008. No. 171. p. 14.

Fox, G.A., 2007. Estimating streambed conductivity: guidelines for stream-aquifer analysis tests. *American Society of Agricultrual and Biolgical Engineers* 50(1): 107-113.

Fox, G.A., and L. Gordji, 2007. Consideration for unsaturated flow beneath a streambed during alluvial well depletion. *Journal of Hydrologic Engineering*. 12(2): 139-145.

Frequently Asked Questions, New Mexico Office of the State Engineer. Available at http://www.ose.state.nm.us/water_info_awrm_admin.html. Accessed 5 June 2008.

Garrick, D, K. Jacobs and G. Garfin, 2008. Models, assumptions, and stakeholders: planning for water supply variability in the Colorado River Basin. *Journal of the American Water Resources Association* 44(2): 381-398.

Gehman, C.L., D.L. Harry, W.E. Sanford, J.D. Stednick, and N.A. Beckman, 2009. Estimating specific yield and storage change in an unconfined aquifer using temporal gravity surveys. *Water Resources Research*. 45(0).

Haan, C.T., B.J. Barfield, and J.C. Hayes. 1994. *Design Hydrology and Sedimentology for Small Catchments*. Academic Press, Inc.

Hafi, Ahmed, 2003. Conjunctive use of groundwater and surface water in the Burdekin Delta Area. *The Economic Record.* 79(Special Issue): S52-S62.

Harbaugh, A. W., and McDonald, M.G., 1996. "Users documentation for MODFLOW-96, An update to the U.S.Geological Survey modular finite-difference ground-water model." *U.S. Geological Survey (USGS) Open File Rep. No. 96-485,* USGS, Denver.

Heeren, D.M., G.A. Fox, M.L. Chu-Agor, and G.V. Wilson, 2009. Predicting streambank seepage flows: sensitivity to soil properties and layering. *ASCE EWRI World and Environmental Resources Congress.*

Houston & T.X, .Ry. Co. v. East, 81 S.W. 279 (Texas 1904).

Hutson, S.S., N.L. Barber, J.F. Kenny, D.S. Linsey, D.S. Lumia, and M.A. Maupin, 2000. Estimated use of water in the United States in 2000. U.S. Geological Survey Circular 1268.

Interstate Stream Compacts, OWRB. Available at http://www.owrb.ok.gov/supply/compacts/compacts.php. Accessed 15 January 2008.

Johnson, R.H., 2007. Ground water flow modeling with sensitivity analyses to guide field data collection in a mountain watershed. *Ground Water Monitoring & Remediation* 27(1): 75-83.

Jyrkama, M.I., J.F. Sykes, and S.D. Norman, 2002. Recharge estimation for transient ground watermodeling. *Groundwater*. 40 (6): 638-648.

Larkin, R.G., and J.M. Sharp. 1992. On the relationship between river-basin geomorphology, aquifer hydraulics, and ground-water flow direction in alluvial aquifers. *Geological Soc. Of America Bulletin* 104(12): 1608-1620.

Lee, C.H., H.F. Yeh, and J.F. Chen, 2008. Estimation of groundwater recharge using the soil moisture budget method and the base-flow model. *Environmental Geology.* 54(8).

Looney, J.W., 1989. Water law in Arkansas. Arkansas Soil and Water Conservation Commission.

Mukhopadhyay, A., J. Al-Sulaimi, and J.M. Barrat, 1994. Numerical modeling of ground-water resource management options in Kuwait. *Ground Water* 32(6): 917-927.

New Mexico Water Code. §72.

New Mexico State Water Plan, 2003. Office of the State Engineer/Interstate Stream Commission.

Okla Code. Title 785: Oklahoma Water Resources Board, Chapter 20: Appropriation and Use of Stream Water.

Okla. Statutes. Title 82. Waters and Water Rights.

Office of the State Engineer, 2000. The Impact of and Problems Associated with Domestic Water wells in New Mexico

Office of the State Engineer, 2006. Rules and Regulations Governing the Use of Public Underground Waters for Household or other Domestic Use §19.25.7.

OWRB. Ground Water Studies. Available at http://owrb.ok.gov/studies/groundwater/groundwater.php. Accessed 25 June 2008.

OWRB. Oklahoma Water Facts. Available at http://www.owrb.ok.gov/util/waterfact.php. Accessed 18 June 2008.

OWRB, 1995. Update of the Oklahoma comprehensive water plan. Water law administration.

Pisinaras, V., C. Petalas, V.A. Tsihrintzis, and E. Zagana, 2007. A groundwater flow model for water resources management in the Ismarida plain, North Greece. *Environmental Modeling and Assessment* 12(2): 75-90.

Priority Administration, New Mexico of the State Engineer. Available at http://www.ose.state.nm.us/legal_ose_adjudication.html. Accessed 1 July 2008).

Rejani, R., M.K. Jha, S.N. Panda, and R. Mull, 2008. Simulation modeling for efficient groundwater management in Balasore Coastal Basin, India. *Water Resource Management* 22: 23-50.

Rights to Surface Water in Texas, 2002. Texas Natural Resource Conservation Commission GI-228 (Rev. 3/09)

Rules and Regulations Governing the Appropriation and Use of Ground Water in New Mexico, 2006. Office of the State Engineer. §1-15.6, 1-2.

Schwartz, S., 2006. Whiskey is for drinking, water is for fighting: a Texas perspective on the issues and pressures relating to conflicts over water. The School of Law Texas Tech University. Texas Tech Law Review. 38 Tex. Tech L. Rev. 1011.

Sipriano v. Great Spring Waters of America, et al., 1 SW3d 75 (Texas 1999).

Statisitical Abstract of the United States, 2007.

Surface Water Administration, New Mexico Natural Resources and Wildlife.

TCEQ (Texas Commission on Environmental Quality), TWDB (Texas Water Development Board), 2007. *Priority Groundwater Management Areas and Groundwater Conservation Districts, Report to the 80th Texas Legislature*. SFR-053/05.

Texas Cooperative Extension, 2002. Questions about groundwater conservation districts in Texas, Texas A&M University B-6120.

Texas Groundwater Protection Committee, 2003. Texas groundwater protection strategy. c/o Groundwater Assessment Section, MC-147, Texas Commission on Environmental Quality.

Texas Rainwater Harvesting Evaluation Committee, 2006. Rainwater Harvesting Potential and Guidelines for Texas, Report to the 80th Legislature. Texas Water Development Board. Austin, Texas.

Texas Water Code. Title 2. Water Administration. Chapter 11, Water Rights.

Texas Water Code. Title 2. Water Administration. Chapter 35, Groundwater Studies.

Texas Water Code. Title 2. Water Administration. Chapter 36, Groundwater Conservation Districts.

Texas Water Code. Title 3. River Compacts. Chapters 41, 42, 43, 44, 45.

Texas Water Law. Texas Water Resources Education. Available at http://texaswater.tamu.edu/waterlaw.texas.htm. Accessed 5 August 2007.

Tortorelli, Robert, 2000. Estimated Freshwater Withdrawals in Oklahoma.

Water for Texas, 2007. Chapter 6: Surface Water Resources (p 138). Texas Water Development Board.

APPENDICES

APPENDIX A: SUMMARY OF THE WATER RIGHTS OF ARKANSAS, OKLAHOMA, TEXAS, AND NEW MEXICO

	Arkansas	Oklahoma	Texas	New Mexico
State agency that manages water resources	Arkansas Natural Resources Commission (ANRC)	Oklahoma Water Resources Board (OWRB)	Texas Commission on Environmental Quality (TCEQ)	Office of the State Engineer
Water allocation system	Modified Riparian Doctrine	Hybrid Doctrine	Hybrid Doctrine	Doctrine of Prior Appropriation
Climate/yearly precipitation	Humid/45-64 in/yr	Humid in east, arid in west/less than 18 to 54 in/yr	Humid in the east, arid in the west/less than 14 to 54 in/yr	Arid/12-20 in; more in the mountains
Quantity of Surface Water (mi^2)	1,107 mi^2; 2.09% of total 53,075 mi^2	1,224 mi^2; 1.76% of total 68,679 mi^2	6,687 mi^2; 2.49% of total 268,601 mi^2	234 mi^2; 0.20% of total 121,598 mi^2
Do landowners have the right to capture diffused surface water?	Yes	Yes	Yes	Yes
Who owns surface water?	Public for navigable waters and riparian landowners for non-navigable waters	Public	Public	Public
Do riparian landowners need a permit to divert surface water?	No	Yes, except for domestic use	Yes, except for domestic use	Yes
Do non-riparian landowners need a permit to divert surface water?	Yes	Yes	Yes	Yes
Quantity of surface water that may be diverted by riparian landowners	As much as they need subject to the needs of other riparians	Amount appropriated by the OWRB based on availability	Amount appropriated by the TCEQ based on availability	Amount appropriated by the State Engineer based on availability

Quantity of surface water that may be diverted by non-riparian landowners	Amount appropriated by the ANRC based on "excess" water	Same as above	Same as above	Same as above
Who receives water during a water shortage?	Domestic users by followed by registered riparian landowners	Domestic users followed by senior right holders	Domestic users followed by senior right holders	Senior right holders
Preference given in the allocation of surface water	Yes	No	Yes	No
Number of years of non-use to lose permit	Riparian-cannot lose right; non-riparian-two	Seven	Three	Four
Owner of ground water	For non-riparian irrigation permits	Landowners	Landowners	Public
Permit required for domestic use	No	No	No	Yes
Permit required for other uses	No	Yes	In some groundwater conservation districts	Yes
Quantity of water that may be withdrawn	The amount needed for beneficial use subject to other competing users	Two-acre feet of water for each acre-foot of land owned; more or less in studied basins	No limit except in conservation districts (quantity varies)	Quantity available and needed for beneficial use
Meter Required	For wells in all sustaining aquifers	No	In some groundwater conservation districts	In water master districts, for new domestic wells for multiple households, and in domestic well management areas

APPENDIX B: MODFLOW MODEL SETUP

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MODFLOW
     U.S. GEOLOGICAL SURVEY MODULAR FINITE-DIFFERENCE GROUND-
WATER FLOW MODEL



 THE FREE FORMAT OPTION HAS BEEN SELECTED
    1 LAYERS        50 ROWS       250 COLUMNS
  40 STRESS PERIOD(S) IN SIMULATION
 MODEL TIME UNIT IS DAYS

 BAS5 -- BASIC MODEL PACKAGE, VERSION 5, 1/1/95 INPUT READ FROM
UNIT  1
 ARRAYS RHS AND BUFF WILL HAVE SEPARATE MEMORY ALLOCATIONS
 INITIAL HEAD WILL BE KEPT THROUGHOUT THE SIMULATION
     125304 ELEMENTS IN X ARRAY ARE USED BY BAS
     125304 ELEMENTS OF X ARRAY USED OUT OF   20000000

 BCF5 -- BLOCK-CENTERED FLOW PACKAGE, VERSION 5, 9/1/93 INPUT READ
FROM UNIT 11
 TRANSIENT SIMULATION
 CELL-BY-CELL FLOWS WILL BE SAVED ON UNIT 50
 HEAD AT CELLS THAT CONVERT TO DRY= -0.10000E+31
 WETTING CAPABILITY IS NOT ACTIVE
      LAYER  LAYER-TYPE CODE     INTERBLOCK T
      --------------------------------------------
         1           1          0 -- HARMONIC
      37501 ELEMENTS IN X ARRAY ARE USED BY BCF
     162805 ELEMENTS OF X ARRAY USED OUT OF   20000000

 WEL5 -- WELL PACKAGE, VERSION 5, 9/1/93 INPUT READ FROM UNIT 12
 MAXIMUM OF  494 WELLS
 CELL-BY-CELL FLOWS WILL BE SAVED ON UNIT 50
       1976 ELEMENTS IN X ARRAY ARE USED BY WEL
     164781 ELEMENTS OF X ARRAY USED OUT OF   20000000

 RIV5 -- RIVER PACKAGE, VERSION 5, 9/1/93 INPUT READ FROM UNIT 14
 MAXIMUM OF  246 RIVER REACHES
 CELL-BY-CELL FLOWS WILL BE SAVED ON UNIT 50
       1476 ELEMENTS IN X ARRAY ARE USED BY RIV
     166257 ELEMENTS OF X ARRAY USED OUT OF   20000000

 RCH5 -- RECHARGE PACKAGE, VERSION 5, 6/1/95 INPUT READ FROM UNIT
18
 OPTION 1 -- RECHARGE TO TOP LAYER
 CELL-BY-CELL FLOWS WILL BE SAVED ON UNIT 50
```

12500 ELEMENTS IN X ARRAY ARE USED BY RCH
178757 ELEMENTS OF X ARRAY USED OUT OF 20000000
0PCG2 -- CONJUGATE GRADIENT SOLUTION PACKAGE, VERSION 2.1, 6/1/95
MAXIMUM OF 50 CALLS OF SOLUTION ROUTINE
MAXIMUM OF 30 INTERNAL ITERATIONS PER CALL TO SOLUTION ROUTINE
MATRIX PRECONDITIONING TYPE : 1
63500 ELEMENTS IN X ARRAY ARE USED BY PCG
242257 ELEMENTS OF X ARRAY USED OUT OF*******
1

BOUNDARY ARRAY FOR LAYER 1
READING ON UNIT 1 WITH FORMAT: (5I3)

AQUIFER HEAD WILL BE SET TO -999.99 AT ALL NO-FLOW NODES (IBOUND=0).

INITIAL HEAD FOR LAYER 1
READING ON UNIT 1 WITH FORMAT: (5G14.0)

OUTPUT CONTROL IS SPECIFIED EVERY TIME STEP
HEAD PRINT FORMAT CODE IS 0 DRAWDOWN PRINT FORMAT CODE IS 0
HEADS WILL BE SAVED ON UNIT 51 DRAWDOWNS WILL BE SAVED ON UNIT 52

COLUMN TO ROW ANISOTROPY
READING ON UNIT 11 WITH FORMAT: (1G14.0)

DELR
READING ON UNIT 11 WITH FORMAT: (5G14.0)

DELC
READING ON UNIT 11 WITH FORMAT: (5G14.0)

PRIMARY STORAGE COEF = 0.2500000 FOR LAYER 1

HYD. COND. ALONG ROWS = 30.00000 FOR LAYER 1

BOTTOM FOR LAYER 1
READING ON UNIT 11 WITH FORMAT: (5G14.0)
0

SOLUTION BY THE CONJUGATE-GRADIENT METHOD
----
0 MAXIMUM NUMBER OF CALLS TO PCG ROUTINE = 50
MAXIMUM ITERATIONS PER CALL TO PCG = 30
MATRIX PRECONDITIONING TYPE = 1
RELAXATION FACTOR (ONLY USED WITH PRECOND. TYPE 1) = 0.10000E+01
PARAMETER OF POLYMOMIAL PRECOND. = 2 (2) OR IS CALCULATED : 1
HEAD CHANGE CRITERION FOR CLOSURE = 0.10000E-02
RESIDUAL CHANGE CRITERION FOR CLOSURE = 0.10000E-02
PCG HEAD AND RESIDUAL CHANGE PRINTOUT INTERVAL = 1
PRINTING FROM SOLVER IS LIMITED(1) OR SUPPRESSED (>1) = 0
DAMPING PARAMETER = 0.10000E+01
1
STRESS PERIOD NO. 1, LENGTH = 100.0000

NUMBER OF TIME STEPS = 50

MULTIPLIER FOR DELT = 1.000

INITIAL TIME STEP SIZE = 2.000000

494 WELLS

LAYER	ROW	COL	STRESS RATE	WELL NO.
1	1	127	1270.0	1
1	2	74	-1270.0	2
1	3	47	-1270.0	3
1	3	96	-1270.0	4

1	3	114	-1270.0	5
1	3	237	-1270.0	6
1	4	38	-1270.0	7
1	4	71	-1270.0	8
1	4	75	-1270.0	9
1	5	6	-1270.0	10
1	5	20	-1270.0	11
1	5	61	-1270.0	12
1	5	121	-1270.0	13
1	5	176	-1270.0	14
1	5	200	-1270.0	15
1	6	30	-1270.0	16
1	6	180	-1270.0	17
1	7	80	-1270.0	18
1	7	136	-1270.0	19
1	7	197	-1270.0	20
1	8	10	-1270.0	21
1	8	16	-1270.0	22
1	8	33	-1270.0	23
1	8	93	-1270.0	24
1	8	154	-1270.0	25
1	8	197	- 1270.0	26
1	8	247	-1270.0	27
1	9	22	-1270.0	28
1	9	27	-1270.0	29
1	9	71	-1270.0	30
1	9	128	-1270.0	31
1	9	138	-1270.0	32
1	9	140	-1270.0	33
1	9	214	- 1270.0	34
1	9	241	-1270.0	35
1	10	3	-1270.0	36
1	10	122	-1270.0	37
1	10	142	-1270.0	38
1	10	191	-1270.0	39
1	10	203	-1270.0	40
1	11	32	-1270.0	41
1	11	45	-1270.0	42
1	11	49	-1270.0	43
1	11	141	-1270.0	44
1	11	229	-1270.0	45
1	11	231	-1270.0	46
1	12	34	-1270.0	47
1	12	54	-1270.0	48
1	12	71	-1270.0	49
1	12	152	-1270.0	50

1	13	1	-1270.0	51
1	13	66	-1270.0	52
1	13	84	-1270.0	53
1	13	97	-1270.0	54
1	13	102	-1270.0	55
1	13	155	-1270.0	56
1	13	161	-1270.0	57
1	13	176	-1270.0	58
1	13	181	-1270.0	59
1	13	185	-1270.0	60
1	13	217	-1270.0	61
1	14	29	-1270.0	62
1	14	59	-1270.0	63
1	14	72	-1270.0	64
1	14	78	-1270.0	65
1	14	107	-1270.0	66
1	14	145	-1270.0	67
1	14	157	-1270.0	68
1	15	9	-1270.0	69
1	15	23	-1270.0	70
1	15	28	-1270.0	71
1	15	38	-1270.0	72
1	15	134	-1270.0	73
1	15	155	-1270.0	74
1	15	170	-1270.0	75
1	15	193	-1270.0	76
1	15	196	-1270.0	77
1	15	221	-1270.0	78
1	15	225	-1270.0	79
1	15	233	-1270.0	80
1	15	242	-1270.0	81
1	16	30	-1270.0	82
1	16	65	-1270.0	83
1	16	91	-1270.0	84
1	16	122	-1270.0	85
1	16	126	-1270.0	86
1	16	127	-1270.0	87
1	16	135	-1270.0	88
1	16	138	-1270.0	89
1	16	155	-1270.0	90
1	16	164	-1270.0	91
1	16	247	-1270.0	92
1	17	2	-1270.0	93
1	17	12	-1270.0	94
1	17	42	-1270.0	95
1	17	49	-1270.0	96

1	17	61	-1270.0	97
1	17	110	-1270.0	98
1	17	111	-1270.0	99
1	17	115	-1270.0	100
1	17	134	-1270.0	101
1	17	154	-1270.0	102
1	17	189	-1270.0	103
1	17	214	-1270.0	104
1	17	230	-1270.0	105
1	17	236	-1270.0	106
1	18	18	-1270.0	107
1	18	35	-1270.0	108
1	18	55	-1270.0	109
1	18	56	-1270.0	110
1	18	64	-1270.0	111
1	18	192	-1270.0	112
1	18	205	-1270.0	113
1	19	4	-1270.0	114
1	19	25	-1270.0	115
1	19	66	-1270.0	116
1	19	71	-1270.0	117
1	19	73	-1270.0	118
1	19	145	-1270.0	119
1	19	169	-1270.0	120
1	19	208	-1270.0	121
1	20	88	-1270.0	122
1	20	127	-1270.0	123
1	20	180	-1270.0	124
1	20	198	-1270.0	125
1	20	202	-1270.0	126
1	20	213	-1270.0	127
1	20	214	-1270.0	128
1	20	220	-1270.0	129
1	20	242	-1270.0	130
1	21	3	-1270.0	131
1	21	13	-1270.0	132
1	21	66	-1270.0	133
1	21	79	-1270.0	134
1	21	103	-1270.0	135
1	21	107	-1270.0	136
1	21	125	-1270.0	137
1	21	129	-1270.0	138
1	21	141	-1270.0	139
1	21	164	-1270.0	140
1	21	176	-1270.0	141
1	21	178	-1270.0	142

1	21	188	-1270.0	143
1	21	211	-1270.0	144
1	21	217	-1270.0	145
1	22	10	-1270.0	146
1	22	21	-1270.0	147
1	22	54	-1270.0	148
1	22	72	-1270.0	149
1	22	74	-1270.0	150
1	22	95	-1270.0	151
1	22	231	-1270.0	152
1	22	240	-1270.0	153
1	23	2	-1270.0	154
1	23	3	-1270.0	155
1	23	43	-1270.0	156
1	23	70	-1270.0	157
1	23	73	-1270.0	158
1	23	84	-1270.0	159
1	23	121	-1270.0	160
1	23	136	-1270.0	161
1	23	235	-1270.0	162
1	23	240	-1270.0	163
1	24	4	-1270.0	164
1	24	11	-1270.0	165
1	24	19	-1270.0	166
1	24	39	-1270.0	167
1	24	59	-1270.0	168
1	24	65	-1270.0	169
1	24	77	-1270.0	170
1	24	96	-1270.0	171
1	24	161	-1270.0	172
1	24	180	-1270.0	173
1	24	239	-1270.0	174
1	24	247	-1270.0	175
1	25	2	-1270.0	176
1	25	27	-1270.0	177
1	25	31	-1270.0	178
1	25	80	-1270.0	179
1	25	91	-1270.0	180
1	25	134	-1270.0	181
1	25	145	-1270.0	182
1	25	154	-1270.0	183
1	25	164	-1270.0	184
1	25	171	-1270.0	185
1	25	188	-1270.0	186
1	25	207	-1270.0	187
1	25	214	-1270.0	188

1	25	217	-1270.0	189
1	25	220	-1270.0	190
1	26	3	-1270.0	191
1	26	110	-1270.0	192
1	26	175	-1270.0	193
1	26	196	-1270.0	194
1	27	13	-1270.0	195
1	27	34	-1270.0	196
1	27	35	-1270.0	197
1	27	36	-1270.0	198
1	27	62	-1270.0	199
1	27	84	-1270.0	200
1	27	135	-1270.0	201
1	27	137	-1270.0	202
1	27	225	-1270.0	203
1	27	226	-1270.0	204
1	27	228	-1270.0	205
1	27	248	-1270.0	206
1	28	46	-1270.0	207
1	28	48	-1270.0	208
1	28	51	-1270.0	209
1	28	78	-1270.0	210
1	28	152	-1270.0	211
1	28	164	-1270.0	212
1	28	187	-1270.0	213
1	28	218	-1270.0	214
1	29	29	-1270.0	215
1	29	59	-1270.0	216
1	29	74	-1270.0	217
1	29	140	-1270.0	218
1	29	152	-1270.0	219
1	29	182	-1270.0	220
1	29	190	-1270.0	221
1	29	207	-1270.0	222
1	29	210	-1270.0	223
1	29	220	-1270.0	224
1	30	13	-1270.0	225
1	30	66	-1270.0	226
1	30	97	-1270.0	227
1	30	124	-1270.0	228
1	30	166	-1270.0	229
1	30	201	-1270.0	230
1	30	207	-1270.0	231
1	30	215	-1270.0	232
1	30	218	-1270.0	233
1	30	241	-1270.0	234

1	30	246	-1270.0	235
1	31	47	-1270.0	236
1	31	56	-1270.0	237
1	31	71	-1270.0	238
1	31	79	-1270.0	239
1	31	94	-1270.0	240
1	31	192	-1270.0	241
1	31	199	-1270.0	242
1	31	223	-1270.0	243
1	32	9	-1270.0	244
1	32	10	-1270.0	245
1	32	22	-1270.0	246
1	32	44	-1270.0	247
1	32	74	-1270.0	248
1	32	79	-1270.0	249
1	32	83	-1270.0	250
1	32	101	-1270.0	251
1	32	113	-1270.0	252
1	32	122	-1270.0	253
1	32	160	-1270.0	254
1	32	187	-1270.0	255
1	32	189	-1270.0	256
1	32	197	-1270.0	257
1	32	200	-1270.0	258
1	32	210	-1270.0	259
1	32	238	-1270.0	260
1	33	20	-1270.0	261
1	33	68	-1270.0	262
1	33	76	-1270.0	263
1	33	92	-1270.0	264
1	33	109	-1270.0	265
1	33	125	-1270.0	266
1	33	126	-1270.0	267
1	33	134	-1270.0	268
1	33	191	-1270.0	269
1	33	208	-1270.0	270
1	33	211	-1270.0	271
1	33	213	-1270.0	272
1	33	225	-1270.0	273
1	33	233	-1270.0	274
1	33	248	-1270.0	275
1	34	13	-1270.0	276
1	34	26	-1270.0	277
1	34	28	-1270.0	278
1	34	31	-1270.0	279
1	34	34	-1270.0	280

1	34	37	-1270.0	281
1	34	50	-1270.0	282
1	34	83	-1270.0	283
1	34	90	-1270.0	284
1	34	110	-1270.0	285
1	34	120	-1270.0	286
1	34	151	-1270.0	287
1	34	187	-1270.0	288
1	34	198	-1270.0	289
1	34	201	-1270.0	290
1	34	223	-1270.0	291
1	34	247	-1270.0	292
1	35	15	-1270.0	293
1	35	18	-1270.0	294
1	35	20	-1270.0	295
1	35	24	-1270.0	296
1	35	45	-1270.0	297
1	35	53	-1270.0	298
1	35	61	-1270.0	299
1	35	65	-1270.0	300
1	35	74	-1270.0	301
1	35	95	- 1270.0	302
1	35	98	-1270.0	303
1	35	145	-1270.0	304
1	35	150	-1270.0	305
1	35	168	-1270.0	306
1	35	189	-1270.0	307
1	35	195	-1270.0	308
1	35	197	-1270.0	309
1	35	200	-1270.0	310
1	35	201	-1270.0	311
1	35	203	-1270.0	312
1	35	209	-1270.0	313
1	35	223	-1270.0	314
1	35	226	-1270.0	315
1	35	232	-1270.0	316
1	36	4	-1270.0	317
1	36	9	-1270.0	318
1	36	11	-1270.0	319
1	36	28	-1270.0	320
1	36	39	-1270.0	321
1	36	41	-1270.0	322
1	36	72	-1270.0	323
1	36	78	-1270.0	324
1	36	90	-1270.0	325
1	36	93	-1270.0	326

1	36	106	-1270.0	327
1	36	121	-1270.0	328
1	36	128	-1270.0	329
1	36	130	-1270.0	330
1	36	137	-1270.0	331
1	36	143	-1270.0	332
1	36	173	-1270.0	333
1	36	191	-1270.0	334
1	36	192	-1270.0	335
1	36	217	-1270.0	336
1	36	222	-1270.0	337
1	36	224	-1270.0	338
1	36	233	-1270.0	339
1	36	243	-1270.0	340
1	37	7	-1270.0	341
1	37	18	-1270.0	342
1	37	34	-1270.0	343
1	37	53	-1270.0	344
1	37	64	-1270.0	345
1	37	67	-1270.0	346
1	37	69	-1270.0	347
1	37	75	-1270.0	348
1	37	117	-1270.0	349
1	37	119	-1270.0	350
1	37	130	-1270.0	351
1	37	138	-1270.0	352
1	37	149	-1270.0	353
1	37	168	-1270.0	354
1	37	181	-1270.0	355
1	37	187	-1270.0	356
1	37	215	-1270.0	357
1	37	231	-1270.0	358
1	37	240	-1270.0	359
1	38	21	-1270.0	360
1	38	27	-1270.0	361
1	38	58	-1270.0	362
1	38	82	-1270.0	363
1	38	84	-1270.0	364
1	38	86	-1270.0	365
1	38	101	-1270.0	366
1	38	136	-1270.0	367
1	38	153	-1270.0	368
1	38	162	-1270.0	369
1	38	168	-1270.0	370
1	38	188	-1270.0	371
1	38	190	-1270.0	372

1	38	198	-1270.0	373
1	38	221	-1270.0	374
1	38	223	-1270.0	375
1	38	225	-1270.0	376
1	38	226	-1270.0	377
1	38	233	-1270.0	378
1	39	11	-1270.0	379
1	39	14	-1270.0	380
1	39	16	-1270.0	381
1	39	24	-1270.0	382
1	39	29	-1270.0	383
1	39	47	-1270.0	384
1	39	80	-1270.0	385
1	39	98	- 1270.0	386
1	39	102	-1270.0	387
1	39	118	-1270.0	388
1	39	120	-1270.0	389
1	39	121	-1270.0	390
1	39	159	-1270.0	391
1	39	165	-1270.0	392
1	39	174	-1270.0	393
1	39	198	-1270.0	394
1	39	202	-1270.0	395
1	39	211	-1270.0	396
1	39	247	-1270.0	397
1	40	19	-1270.0	398
1	40	28	-1270.0	399
1	40	81	-1270.0	400
1	40	83	-1270.0	401
1	40	111	-1270.0	402
1	40	133	-1270.0	403
1	40	156	-1270.0	404
1	40	175	-1270.0	405
1	40	211	-1270.0	406
1	40	228	-1270.0	407
1	40	241	-1270.0	408
1	40	248	-1270.0	409
1	41	29	-1270.0	410
1	41	32	-1270.0	411
1	41	33	-1270.0	412
1	41	38	-1270.0	413
1	41	69	-1270.0	414
1	41	82	-1270.0	415
1	41	120	-1270.0	416
1	41	163	-1270.0	417
1	41	165	-1270.0	418

1	41	168	-1270.0	419
1	41	170	-1270.0	420
1	41	180	-1270.0	421
1	41	208	-1270.0	422
1	41	217	-1270.0	423
1	41	223	-1270.0	424
1	41	236	-1270.0	425
1	41	247	-1270.0	426
1	42	8	-1270.0	427
1	42	21	-1270.0	428
1	42	42	-1270.0	429
1	42	65	-1270.0	430
1	42	79	-1270.0	431
1	42	84	-1270.0	432
1	42	105	-1270.0	433
1	42	106	-1270.0	434
1	42	111	-1270.0	435
1	42	140	-1270.0	436
1	42	156	-1270.0	437
1	42	165	-1270.0	438
1	42	194	-1270.0	439
1	42	214	-1270.0	440
1	43	36	-1270.0	441
1	43	42	-1270.0	442
1	43	53	-1270.0	443
1	43	56	-1270.0	444
1	43	160	-1270.0	445
1	43	163	-1270.0	446
1	43	206	-1270.0	447
1	44	43	-1270.0	448
1	44	83	-1270.0	449
1	44	95	-1270.0	450
1	44	103	-1270.0	451
1	44	128	-1270.0	452
1	44	138	-1270.0	453
1	44	142	-1270.0	454
1	44	147	-1270.0	455
1	44	155	-1270.0	456
1	44	157	-1270.0	457
1	44	187	-1270.0	458
1	44	212	-1270.0	459
1	44	226	-1270.0	460
1	45	19	-1270.0	461
1	45	81	-1270.0	462
1	45	106	-1270.0	463
1	45	110	-1270.0	464

1	45	117	-1270.0	465
1	45	128	-1270.0	466
1	45	151	-1270.0	467
1	45	221	-1270.0	468
1	45	233	-1270.0	469
1	45	237	-1270.0	470
1	46	7	-1270.0	471
1	46	13	-1270.0	472
1	46	63	-1270.0	473
1	46	72	-1270.0	474
1	46	73	-1270.0	475
1	46	74	-1270.0	476
1	46	75	-1270.0	477
1	46	83	-1270.0	478
1	46	128	-1270.0	479
1	46	139	-1270.0	480
1	46	140	-1270.0	481
1	46	157	-1270.0	482
1	46	191	-1270.0	483
1	46	200	-1270.0	484
1	46	201	-1270.0	485
1	47	34	-1270.0	486
1	47	52	-1270.0	487
1	47	70	-1270.0	488
1	47	132	-1270.0	489
1	48	138	-1270.0	490
1	48	166	-1270.0	491
1	49	38	-1270.0	492
1	49	57	-1270.0	493
1	49	79	-1270.0	494

246 RIVER REACHES

LAYER	ROW	COL	STAGE	CONDUCTANCE	BOT. ELEV.	REACH NO.
1	37	3	114.9	5484.	111.9	1
1	37	4	114.6	0.1200E+05	111.6	2
1	37	5	114.2	0.1200E+05	111.2	3
1	37	6	113.8	0.1200E+05	110.8	4
1	37	7	113.4	0.1200E+05	110.4	5
1	37	8	112.9	0.1200E+05	109.9	6
1	37	9	112.5	0.1200E+05	109.5	7
1	37	10	112.1	0.1200E+05	109.1	8
1	37	11	111.7	0.1200E+05	108.7	9
1	37	12	111.3	0.1200E+05	108.3	10

1	37	13	110.9	0.1200E+05	107.9	11
1	37	14	110.4	0.1200E+05	107.4	12
1	37	15	110.0	0.1200E+05	107.0	13
1	37	16	109.6	0.1200E+05	106.6	14
1	37	17	109.2	0.1200E+05	106.2	15
1	37	18	108.8	0.1200E+05	105.8	16
1	37	19	108.4	0.1200E+05	105.4	17
1	37	20	107.9	0.1200E+05	104.9	18
1	37	21	107.5	0.1200E+05	104.5	19
1	37	22	107.1	0.1200E+05	104.1	20
1	37	23	106.7	0.1200E+05	103.7	21
1	37	24	106.3	0.1200E+05	103.3	22
1	37	25	105.9	0.1200E+05	102.9	23
1	37	26	105.5	0.1200E+05	102.5	24
1	37	27	105.0	0.1200E+05	102.0	25
1	37	28	104.6	0.1200E+05	101.6	26
1	37	29	104.2	0.1200E+05	101.2	27
1	37	30	103.8	0.1200E+05	100.8	28
1	37	31	103.4	0.1200E+05	100.4	29
1	37	32	103.0	0.1200E+05	99.96	30
1	37	33	102.5	0.1200E+05	99.54	31
1	37	34	102.1	0.1200E+05	99.13	32
1	37	35	101.7	0.1200E+05	98.71	33
1	37	36	101.3	0.1200E+05	98.30	34
1	37	37	100.9	0.1200E+05	97.88	35
1	37	38	100.5	0.1200E+05	97.46	36
1	37	39	100.0	0.1200E+05	97.05	37
1	37	40	99.63	0.1200E+05	96.63	38
1	37	41	99.22	0.1200E+05	96.22	39
1	37	42	98.80	0.1200E+05	95.80	40
1	37	43	98.39	0.1200E+05	95.39	41
1	37	44	97.97	0.1200E+05	94.97	42
1	37	45	97.55	0.1200E+05	94.55	43
1	37	46	97.14	0.1200E+05	94.14	44
1	37	47	96.72	0.1200E+05	93.72	45
1	37	48	96.31	0.1200E+05	93.31	46
1	37	49	95.89	0.1200E+05	92.89	47
1	37	50	95.47	0.1200E+05	92.47	48
1	37	51	95.06	0.1200E+05	92.06	49
1	37	52	94.64	0.1200E+05	91.64	50
1	37	53	94.23	0.1200E+05	91.23	51
1	37	54	93.81	0.1200E+05	90.81	52
1	37	55	93.40	0.1200E+05	90.40	53
1	37	56	92.98	0.1200E+05	89.98	54
1	37	57	92.56	0.1200E+05	89.56	55
1	37	58	92.15	0.1200E+05	89.15	56

1	37	59	91.73	0.1200E+05	88.73	57
1	37	60	91.32	0.1200E+05	88.32	58
1	37	61	90.90	0.1200E+05	87.90	59
1	37	62	90.49	0.1200E+05	87.49	60
1	37	63	90.07	0.1200E+05	87.07	61
1	37	64	89.65	0.1200E+05	86.65	62
1	37	65	89.24	0.1200E+05	86.24	63
1	37	66	88.82	0.1200E+05	85.82	64
1	37	67	88.41	0.1200E+05	85.41	65
1	37	68	87.99	0.1200E+05	84.99	66
1	37	69	87.57	0.1200E+05	84.57	67
1	37	70	87.16	0.1200E+05	84.16	68
1	37	71	86.74	0.1200E+05	83.74	69
1	37	72	86.33	0.1200E+05	83.33	70
1	37	73	85.91	0.1200E+05	82.91	71
1	37	74	85.50	0.1200E+05	82.50	72
1	37	75	85.08	0.1200E+05	82.08	73
1	37	76	84.66	0.1200E+05	81.66	74
1	37	77	84.25	0.1200E+05	81.25	75
1	37	78	83.83	0.1200E+05	80.83	76
1	37	79	83.42	0.1200E+05	80.42	77
1	37	80	83.00	0.1200E+05	80.00	78
1	37	81	82.58	0.1200E+05	79.58	79
1	37	82	82.17	0.1200E+05	79.17	80
1	37	83	81.75	0.1200E+05	78.75	81
1	37	84	81.34	0.1200E+05	78.34	82
1	37	85	80.92	0.1200E+05	77.92	83
1	37	86	80.51	0.1200E+05	77.51	84
1	37	87	80.09	0.1200E+05	77.09	85
1	37	88	79.67	0.1200E+05	76.67	86
1	37	89	79.26	0.1200E+05	76.26	87
1	37	90	78.84	0.1200E+05	75.84	88
1	37	91	78.43	0.1200E+05	75.43	89
1	37	92	78.01	0.1200E+05	75.01	90
1	37	93	77.60	0.1200E+05	74.60	91
1	37	94	77.18	0.1200E+05	74.18	92
1	37	95	76.76	0.1200E+05	73.76	93
1	37	96	76.35	0.1200E+05	73.35	94
1	37	97	75.93	0.1200E+05	72.93	95
1	37	98	75.52	0.1200E+05	72.52	96
1	37	99	75.10	0.1200E+05	72.10	97
1	37	100	74.68	0.1200E+05	71.68	98
1	37	101	74.27	0.1200E+05	71.27	99
1	37	102	73.85	0.1200E+05	70.85	100
1	37	103	73.44	0.1200E+05	70.44	101
1	37	104	73.02	0.1200E+05	70.02	102

1	37	105	72.61	0.1200E+05	69.61	103
1	37	106	72.19	0.1200E+05	69.19	104
1	37	107	71.77	0.1200E+05	68.77	105
1	37	108	71.36	0.1200E+05	68.36	106
1	37	109	70.94	0.1200E+05	67.94	107
1	37	110	70.53	0.1200E+05	67.53	108
1	37	111	70.11	0.1200E+05	67.11	109
1	37	112	69.69	0.1200E+05	66.69	110
1	37	113	69.28	0.1200E+05	66.28	111
1	37	114	68.86	0.1200E+05	65.86	112
1	37	115	68.45	0.1200E+05	65.45	113
1	37	116	68.03	0.1200E+05	65.03	114
1	37	117	67.62	0.1200E+05	64.62	115
1	37	118	67.20	0.1200E+05	64.20	116
1	37	119	66.78	0.1200E+05	63.78	117
1	37	120	66.37	0.1200E+05	63.37	118
1	37	121	65.95	0.1200E+05	62.95	119
1	37	122	65.54	0.1200E+05	62.54	120
1	37	123	65.12	0.1200E+05	62.12	121
1	37	124	64.71	0.1200E+05	61.71	122
1	37	125	64.29	0.1200E+05	61.29	123
1	37	126	63.87	0.1200E+05	60.87	124
1	37	127	63.46	0.1200E+05	60.46	125
1	37	128	63.04	0.1200E+05	60.04	126
1	37	129	62.63	0.1200E+05	59.63	127
1	37	130	62.21	0.1200E+05	59.21	128
1	37	131	61.79	0.1200E+05	58.79	129
1	37	132	61.38	0.1200E+05	58.38	130
1	37	133	60.96	0.1200E+05	57.96	131
1	37	134	60.55	0.1200E+05	57.55	132
1	37	135	60.13	0.1200E+05	57.13	133
1	37	136	59.72	0.1200E+05	56.72	134
1	37	137	59.30	0.1200E+05	56.30	135
1	37	138	58.88	0.1200E+05	55.88	136
1	37	139	58.47	0.1200E+05	55.47	137
1	37	140	58.05	0.1200E+05	55.05	138
1	37	141	57.64	0.1200E+05	54.64	139
1	37	142	57.22	0.1200E+05	54.22	140
1	37	143	56.80	0.1200E+05	53.80	141
1	37	144	56.39	0.1200E+05	53.39	142
1	37	145	55.97	0.1200E+05	52.97	143
1	37	146	55.56	0.1200E+05	52.56	144
1	37	147	55.14	0.1200E+05	52.14	145
1	37	148	54.73	0.1200E+05	51.73	146
1	37	149	54.31	0.1200E+05	51.31	147
1	37	150	53.89	0.1200E+05	50.89	148

1	37	151	53.48	0.1200E+05	50.48	149
1	37	152	53.06	0.1200E+05	50.06	150
1	37	153	52.65	0.1200E+05	49.65	151
1	37	154	52.23	0.1200E+05	49.23	152
1	37	155	51.81	0.1200E+05	48.81	153
1	37	156	51.40	0.1200E+05	48.40	154
1	37	157	50.98	0.1200E+05	47.98	155
1	37	158	50.57	0.1200E+05	47.57	156
1	37	159	50.15	0.1200E+05	47.15	157
1	37	160	49.74	0.1200E+05	46.74	158
1	37	161	49.32	0.1200E+05	46.32	159
1	37	162	48.90	0.1200E+05	45.90	160
1	37	163	48.49	0.1200E+05	45.49	161
1	37	164	48.07	0.1200E+05	45.07	162
1	37	165	47.66	0.1200E+05	44.66	163
1	37	166	47.24	0.1200E+05	44.24	164
1	37	167	46.83	0.1200E+05	43.83	165
1	37	168	46.41	0.1200E+05	43.41	166
1	37	169	45.99	0.1200E+05	42.99	167
1	37	170	45.58	0.1200E+05	42.58	168
1	37	171	45.16	0.1200E+05	42.16	169
1	37	172	44.75	0.1200E+05	41.75	170
1	37	173	44.33	0.1200E+05	41.33	171
1	37	174	43.91	0.1200E+05	40.91	172
1	37	175	43.50	0.1200E+05	40.50	173
1	37	176	43.08	0.1200E+05	40.08	174
1	37	177	42.67	0.1200E+05	39.67	175
1	37	178	42.25	0.1200E+05	39.25	176
1	37	179	41.84	0.1200E+05	38.84	177
1	37	180	41.42	0.1200E+05	38.42	178
1	37	181	41.00	0.1200E+05	38.00	179
1	37	182	40.59	0.1200E+05	37.59	180
1	37	183	40.17	0.1200E+05	37.17	181
1	37	184	39.76	0.1200E+05	36.76	182
1	37	185	39.34	0.1200E+05	36.34	183
1	37	186	38.92	0.1200E+05	35.92	184
1	37	187	38.51	0.1200E+05	35.51	185
1	37	188	38.09	0.1200E+05	35.09	186
1	37	189	37.68	0.1200E+05	34.68	187
1	37	190	37.26	0.1200E+05	34.26	188
1	37	191	36.85	0.1200E+05	33.85	189
1	37	192	36.43	0.1200E+05	33.43	190
1	37	193	36.01	0.1200E+05	33.01	191
1	37	194	35.60	0.1200E+05	32.60	192
1	37	195	35.18	0.1200E+05	32.18	193
1	37	196	34.77	0.1200E+05	31.77	194

1	37	197	34.35	0.1200E+05	31.35	195
1	37	198	33.94	0.1200E+05	30.94	196
1	37	199	33.52	0.1200E+05	30.52	197
1	37	200	33.10	0.1200E+05	30.10	198
1	37	201	32.69	0.1200E+05	29.69	199
1	37	202	32.27	0.1200E+05	29.27	200
1	37	203	31.86	0.1200E+05	28.86	201
1	37	204	31.44	0.1200E+05	28.44	202
1	37	205	31.02	0.1200E+05	28.02	203
1	37	206	30.61	0.1200E+05	27.61	204
1	37	207	30.19	0.1200E+05	27.19	205
1	37	208	29.78	0.1200E+05	26.78	206
1	37	209	29.36	0.1200E+05	26.36	207
1	37	210	28.95	0.1200E+05	25.95	208
1	37	211	28.53	0.1200E+05	25.53	209
1	37	212	28.11	0.1200E+05	25.11	210
1	37	213	27.70	0.1200E+05	24.70	211
1	37	214	27.28	0.1200E+05	24.28	212
1	37	215	26.87	0.1200E+05	23.87	213
1	37	216	26.45	0.1200E+05	23.45	214
1	37	217	26.03	0.1200E+05	23.03	215
1	37	218	25.62	0.1200E+05	22.62	216
1	37	219	25.20	0.1200E+05	22.20	217
1	37	220	24.79	0.1200E+05	21.79	218
1	37	221	24.37	0.1200E+05	21.37	219
1	37	222	23.96	0.1200E+05	20.96	220
1	37	223	23.54	0.1200E+05	20.54	221
1	37	224	23.12	0.1200E+05	20.12	222
1	37	225	22.71	0.1200E+05	19.71	223
1	37	226	22.29	0.1200E+05	19.29	224
1	37	227	21.88	0.1200E+05	18.88	225
1	37	228	21.46	0.1200E+05	18.46	226
1	37	229	21.05	0.1200E+05	18.05	227
1	37	230	20.63	0.1200E+05	17.63	228
1	37	231	20.21	0.1200E+05	17.21	229
1	37	232	19.80	0.1200E+05	16.80	230
1	37	233	19.38	0.1200E+05	16.38	231
1	37	234	18.97	0.1200E+05	15.97	232
1	37	235	18.55	0.1200E+05	15.55	233
1	37	236	18.13	0.1200E+05	15.13	234
1	37	237	17.72	0.1200E+05	14.72	235
1	37	238	17.30	0.1200E+05	14.30	236
1	37	239	16.89	0.1200E+05	13.89	237
1	37	240	16.47	0.1200E+05	13.47	238
1	37	241	16.06	0.1200E+05	13.06	239
1	37	242	15.64	0.1200E+05	12.64	240

1	37	243	15.22	0.1200E+05	12.22	241
1	37	244	14.81	0.1200E+05	11.81	242
1	37	245	14.39	0.1200E+05	11.39	243
1	37	246	13.98	0.1200E+05	10.98	244
1	37	247	13.56	0.1200E+05	10.56	245
1	37	248	13.18	0.1018E+05	10.18	246

RECHARGE = 0.7000000E-04
0
4 CALLS TO PCG ROUTINE FOR TIME STEP 1 IN STRESS PERIOD 1
8 TOTAL ITERATIONS
0MAXIMUM HEAD CHANGE FOR EACH ITERATION (1 INDICATES THE FIRST INNER ITERATION):
0 HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL
----
1 -1.553 (1, 37,222) 0 -0.2074E-02 (1, 36,225) 0 -0.2905E-05 (1, 35,226) 1 0.1730E-01 (1, 9,140)
0 0.2406E-04 (1, 10,139) 1 0.3034E-03 (1, 9,140) 0 0.4202E-06 (1, 10,139) 1 0.5350E-05 (1, 9,140)
0
0MAXIMUM RESIDUAL FOR EACH ITERATION (1 INDICATES THE FIRST INNER ITERATION):
0 RESIDUAL LAYER,ROW,COL RESIDUAL LAYER,ROW,COL RESIDUAL LAYER,ROW,COL RESIDUAL LAYER,ROW,COL
----
1 24.10 (1, 36,225) 0 0.3265E-01 (1, 35,226) 0 -0.4788E-04 (1, 37,248) 1 -0.3064 (1, 10,139)
0 -0.4393E-03 (1, 9,140) 1 -0.5360E-02 (1, 10,139) 0 -0.7171E-05 (1, 11,138) 1 -0.9455E-04 (1, 10,139)
0

HEAD/DRAWDOWN PRINTOUT FLAG = 1 TOTAL BUDGET PRINTOUT FLAG = 1
CELL-BY-CELL FLOW TERM FLAG

VITA

Aaron Ray Mittelstet

Candidate for the Degree of

Master of Science

Thesis: EFFECT OF WATER RIGHTS AND MANAGEMENT POLICIES ON A RIVER ALLUVIAL AQUIFER

Major Field: Environmental Science

Biographical:

Personal Data: Born in Enid, OK on January 24th, 1977

Education: Graduated from Enid High School, Enid, OK in May of 1995; received Bachelor of Science degree in Zoology from Oklahoma State University, Stillwater, OK in May, 2000; completed the requirements for the Master of Science in your Environmental Science at Oklahoma State University, Stillwater, Oklahoma in July, 2009.

Experience: Peace Corp volunteer in Guatemala from 2000-2002; self employed English teacher in Almeria, Spain in 2003; employed by the Enid Public Schools to teach ESL and Spanish from 2004-2007; employed by Oklahoma State University as a research assistant from 2007-2009; employed by Oklahoma State University as a research engineer from 2009-present

Professional Memberships: American Society of Agricultural and Biological Engineers, American Water Resource Association, Audubon Society, Honor Society of Phi-Kappa Phi, The National Scholars Honor Society, Golden Key International Honor Society

Name: Aaron Mittelstet Date of Degree: July, 2009

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: EFFECT OF WATER RIGHTS AND MANAGEMENT POLICIES ON A RIVER ALLUVIAL AQUIFER

Pages in Study: 87 Candidate for the Degree of Master of Science

Major Field: Environmental Science

Scope and Method of Study: The purpose of this study was to analyze the water policies and tools that are available to manage water resources in times of water shortages based on the system of appropriation a state has adopted and the specific rules and regulations of a state. This was completed by:

- comparing the water rights and policies of Arkansas, Oklahoma, Texas, and New Mexico and how they vary from the eastern United States westward.
- using MODFLOW to compare the ground water policies of Oklahoma and the Texas Groundwater Conservation District and how each policy affects an alluvial aquifer-stream system.

Findings and Conclusions: Some tools such as water metering, conservation, and water reuse can be effective in any region whereas others such as permit administration, watermasters, water rotation, water sharing, and water banking are only available to the more flexible appropriation doctrine. Model simulations show that Oklahoma's water policy can limit the decline of the water table where development is low, but the Panhandle Groundwater Conservation District does not. However, as the aquifer becomes more developed, the Panhandle Groundwater Conservation District policy would be more sustainable and the aquifer would not be permitted to go dry. This is because the pumping rate of the Panhandle Groundwater Conservation District policy is revisited every five years, but the Oklahoma policy is not.

Advisor's Approval: ______________________________