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Comparison of Aquifer Sustainability Under Groundwater Administrations in Oklahoma and Texas

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Abstract
We compared two approaches to administration of groundwater law on a hydrologic model of the North Canadian River, an alluvial aquifer in northwestern Oklahoma. Oklahoma limits pumping rates to retain 50% aquifer saturated thickness after 20 years of groundwater use. The Texas Panhandle Groundwater Conservation District's (GCD) rules limit pumping to a rate that consumes no more than 50% of saturated thickness in 50 years, with reevaluation and readjustment of permits every 5 years. Using a hydrologic model (MODFLOW), we simulated river-groundwater interaction and aquifer dynamics under increasing levels of "development" (i.e., increasing groundwater withdrawals). Oklahoma's approach initially would limit groundwater extraction more than the GCD approach, but the GCD approach would be more protective in the long run. Under Oklahoma rules more than half of aquifer storage would be depleted when development reaches 65%. Reevaluation of permits under the Texas Panhandle GCD approach would severely limit pumping as the 50% level is approached. Both Oklahoma and Texas Panhandle GCD approaches would deplete alluvial base flow at approximately 10% development. Results suggest periodic review of permits could protect aquifer storage and river base flow. Modeling total aquifer storage is more sensitive to recharge rate and aquifer hydraulic conductivity than to specific yield, while river leakage is most sensitive to aquifer hydraulic conductivity followed by specific yield.

Keywords: alluvial aquifer, water law, water policy, groundwater management, MODFLOW, groundwater model, groundwater-river interaction, conjunctive use

Introduction

Groundwater is a vital resource for the United States. In 2005, 20% of all water used came from the ground with the majority being used for irrigation (Barber, 2009). Though 80% of our water comes from lakes and rivers, much of it is connected directly to groundwater. Depleting groundwater can reduce the base flow in rivers, which in turn will reduce the quantity of surface water available (Theis, 1940).

Each state appropriates its water resources differently. Some regulate surface and groundwater separately, while others treat the two as one system and manage them conjunctively. Conjunctive use requires surface and groundwater policies to be determined simultaneously (Hafi, 2003). For example, New Mexico recognizes the interaction between surface and groundwater such that a proposed groundwater diversion must not interfere with current surface water rights (N.M. Stat. 72-5-5 and 12-3). In Oklahoma and Texas, the permitting of groundwater is largely done without regard to its effect on surface water availability (Texas Water Code 35.003; Okla. Stat. 82:1020.9) except where such use affects solesource aquifers such as the Edwards Aquifer in Texas or the Arbuckle-Simpson Aquifer in Oklahoma (Edwards Aquifer Authority, 2008; Okla. Stat. 82:1020.9A-B1). In these special cases, both states' surface flows must be considered when granting groundwater withdrawal permits. This is an important feature of the water rights regime that can be incorporated into a hydrological model.

Oklahoma's groundwater law allows landowners or lessees to obtain a permit from the Oklahoma Water Resources Board (OWRB) to use groundwater based on the "number of acres of the applicant's land that overlies a groundwater basin" (Okla. Stat. 82:1020.9). Where studies have not been completed to determine the quantity of water in a groundwater basin, temporary permits are issued (Okla. Stat. 82:1020.11B) that allow the withdrawal of 2 acre-ft/year (2,466 m^3/year) of water for each acre (0.4047 ha) of land owned or leased (Okla. Stat. 82:1020.11B). If a study has been conducted to determine the annual yield for the basin, the maximum withdrawal is based on a minimum basin life of 20 years (Okla. Stat. 82:1020.9). The permitted amount may be more or less than the temporary 2 acre-ft/acre (6,093 m^3/ha). The maximum annual yield is set such that after a minimum of 20 years, 50% of the aquifer will retain a specified minimum saturated thickness: 1.52 m for alluvial 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 groundwater, 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, in 1949 the Texas Legislature passed a law to limit groundwater pumping within the jurisdiction of a groundwater conservation district (GCD) (Texas Groundwater Protection Committee, 2003). The Texas Panhandle Groundwater Conservation District adopted a "50/50" standard, which limits pumping such that 50% of current supplies, or saturated thickness, will still be available in 50 years (Panhandle Groundwater Conservation District, 2005). Further under this standard, the maximum pumping rate is revisited every five years to see if the depletion rate needs to be adjusted (Panhandle Groundwater Conservation District, 2005).

Wells located near a stream can intercept water that normally would have discharged to the stream as base flow. Over time, it is even possible to reverse the hydraulic gradient such that the stream will discharge only to the aquifer rather than to higher magnitude streams (Chen and Yin, 2001). Models can be used to simulate the effect that groundwater pumping has on aquifer storage and hydrologically connected surface water flows. Historically, these models were used primarily to evaluate the physical features of hydrologic systems. As models have improved, researchers and water agency personnel have turned to hydrologic models to simulate the impacts of alternative water policies and inform policy decisions. For example, Mukhopadhyay *et al.* (1994) used the VTDN software to simulate the impacts of four alternative exploitation/development plans on groundwater flow in a Kuwaiti aquifer system. The New Mexico Office of the State Engineer uses groundwater flow models to guide administrative decisions about drawdown effects, and has recently applied MODFLOW to simulate the impacts of groundwater wells on aquifers and streams in 17 basins in the state (Balleau and Silver, 2005). Pisinaras *et al.* (2007) used MODFLOW to study the effect of 87 irrigation wells on a semiconfined aquifer system in North Greece, and simulated the impacts of four management scenarios over 20 years on long-term aquifer response. Rejani *et al.* (2008) used MODFLOW to analyze the aquifer response to five alternative groundwater pumping strategies in India. The simulation results were used to inform a best management strategy for the region.

To date, no study has used hydrologic modeling to compare groundwater management laws and rules like those of Oklahoma and Texas. Below, we simulate the impacts of the Oklahoma and the Texas Panhandle GCD groundwater allocation regimes on a midwestern alluvial aquifer.

Materials and Methods

MODFLOW Model Design

In this study, the groundwater policies of Oklahoma and the Texas Panhandle GCD were compared using a model based on characteristics of the North Canadian

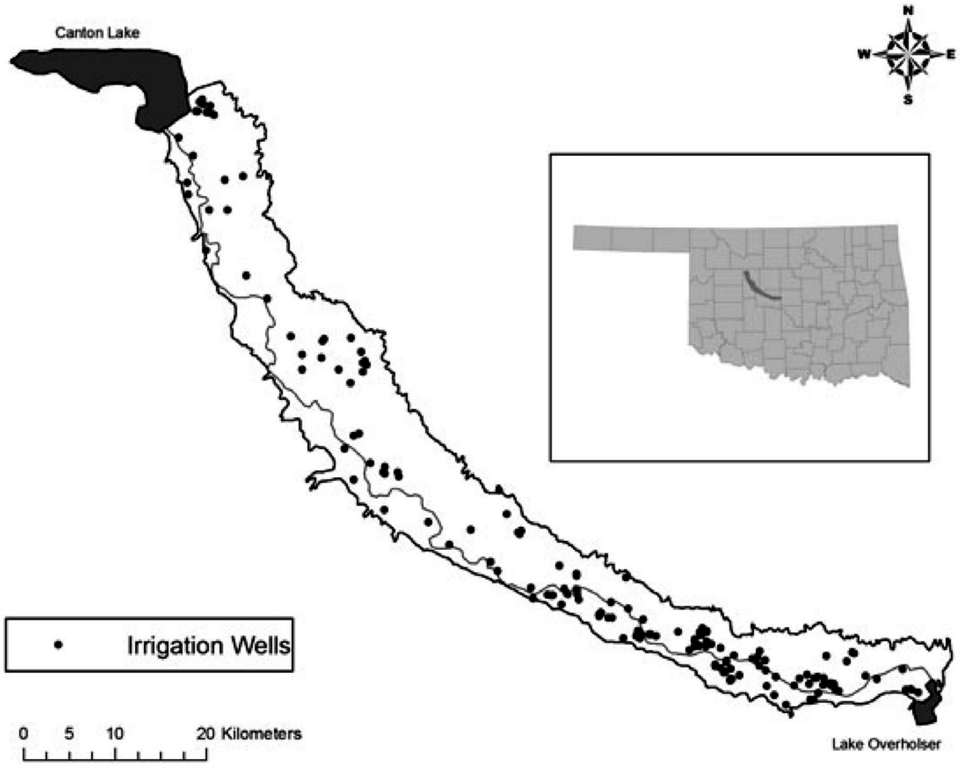

Figure 1. The North Canadian Alluvial Aquifer in Northwest Oklahoma Showing the Location of 150 Existing Irrigation Wells. Canton Lake in the north and Lake Overholser in the south are connected by the North Canadian River.

River Alluvial Aquifer in northwest Oklahoma (Figure 1). The objective was to see which of the two approaches to groundwater administration is more sustainable under increasing aquifer development, where development refers to the rate of new groundwater withdrawals, and to compare the effect of aquifer development on base flow and river leakage. We used MODFLOW's RIVER package, a product of the U.S. Geological Survey (Harbaugh and McDonald, 1996), to simulate the unconfined aquiferstream system (Figure 2).

MODFLOW uses a three-dimensional groundwater 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 is the hydraulic conductivity; x, y, and z are components of the hydraulic conductivity tensor; S^s is specific storage; R is inflow to the system; h is head; and t is time (Anderson and Woessner, 1992). MODFLOW has advantages over analytical models because it takes into account the vertical flow component in the vicinity of the streambed (Chen and Yin, 2001). MODFLOW's streambed conductance, C, is calculated as

$$C = \frac{K_{sb}\, lW}{M} \qquad (2)$$

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

$$\lambda = \frac{C}{l} = \frac{K_{sb}W}{M} \qquad (3)$$

The modeling package *Processing MODFLOW Pro* (Chiang, 2005) was used as an interface for model setup and simulations with model dimensions and parameters from a previous study by Christenson (1983). The aquifer domain was 100 km in length (the x-direction), NW to SE in the North Canadian, and 10 km wide (the y-direction). The model had one homogenous, isotropic layer made up of 12,500 cells (each 80,000 m^2), with the east and west boundaries impermeable. Aquifer thickness was taken as 20 m with a minimum of 19 m uniformly saturated. Constant head boundaries were used to represent the lakes at northwest and southeast ends of the river. The RIVER package, which is used to

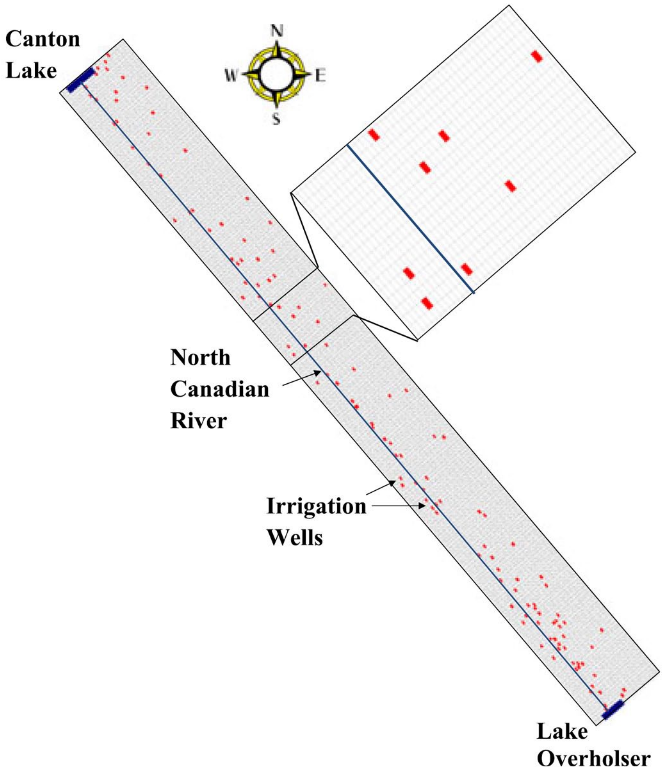

Figure 2. MODFLOW Image Illustrating the North Canadian River, Canton Lake, and Lake Overholser With a Grid of 12,500 Cells and the 247 Simulated Irrigation Wells. Width equals 10 km and length equals 100 km. Zoomed in section of aquifer shown to the right.

calculate the flux of water between the stream and the aquifer, assumes the stream stage remains constant throughout the simulation (Fox and Gordji, 2007). MODFLOW assumes the specific discharge through the streambed, q, is proportional to

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

where s_w is drawdown, defined as the difference between the hydraulic head in the stream and the hydraulic head in the aquifer (Fox and Gordji, 2007). Initially stream stage was set 0.5 m lower than the water table so the stream would gain water from the aquifer. The K was set to 30 m/ day and K_{sb} to 3 m/day or 10% of the aquifer conductivity, with a 1.0 m thickness of streambed. Based on Christenson (1983), specific yield (S_y) was set to 0.25 and R to 2.54 cm/ year.

Sensitivity Analysis

Due to the high cost of measuring model parameters, a sensitivity analysis can indicate the most important input parameters to the simulation (Johnson, 2007). The most critical parameters of the MODFLOW RIVER package related to river leakage and aquifer storage are hydraulic conductivity, specific yield, recharge, and streambed hydraulic conductivity. Hydraulic conductivity (K) can vary significantly based on the size, shape, and connectivity of pores and fractures in the aquifer (Haan *et al.*, 1994). 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). There are three sources of recharge (R) to an alluvial aquifer: precipitation, river leakage, and irrigation return flow. Physical parameters of a model are considered static, as well as groundwater recharge, even though it can be highly variable in space and time (Jyrkama *et al.*, 2002). Streambed conductivity (K_{sb}) can be one to three orders of magnitude lower than aquifer conductivity (Larkin and Sharp, 1992; Calver, 2001; Fox, 2004, 2007).

Sensitivity analysis was performed to evaluate the effect that K, S_y, K_{sb}, and R have on total storage and river leakage. To facilitate simulation of Oklahoma policy, the sensitivity of the parameters was analyzed at 20% aquifer development, or 494 wells, for 20 years. See Table 1 for initial and varied parameter values. A relative sensitivity coefficient, $S_{r(y/x)}$ quantified sensitivity of parameter y relative to input parameter x (Fox *et al.*, 2010):

$$S_{r(y/x)} = \frac{(y - y^b)/y^b}{(x - x^b)/x^b} \tag{5}$$

where y is the output under consideration, y_b is baseline value for output y, and x_b is baseline value for parameter x. Since K and K_{sb} vary by an order of magnitude, these parameters were log transformed. Total storage and stream leakage are y_1 and y_2 and K, S_y, K_{sb}, and R are the input parameters x.

Table 2 shows R was the most sensitive parameter for simulating total storage with a sensitivity coefficient of 0.0553 for both decreasing and increasing values, compared to K with sensitivity of 0.0170 and 0.0731. The value of K had the greatest influence on

Table 1. Initial and Varied Parameter Values for Sensitivity Analysis for the Hydraulic Conductivity (K), Specific Yield (S_y), Recharge (R), and Streambed Hydraulic Conductivity (K_{sb}).

Parameter	Units	Minimum Value	Initial Value	Maximum Value
K	m/day	3.00	30.0	300
S_y	N/A	0.15	0.25	0.35
R	cm/year	1.27	2.54	5.05
K_{sb}	m/day	0.30	3.00	30.0

Table 2. Comparison of Hydraulic Conductivity (K), Specific Yield (S_y), Recharge (R), and Streambed Hydraulic Conductivity (K_{sb}) Sensitivity to Aquifer Storage and River Leakage.

Parameter	Value	Storage Percent Change	Sensitivity Coefficient	River Leakage Percent Change	Sensitivity Coefficient
K (m/day)	3.00	–1.13	0.0170	–44.8	0.687
K (m/day)	300	4.98	0.0731	98.84	1.37
S_y	0.15	2.47	–0.062	23.6	–0.589
S_y	0.35	0.02	0.0006	–16.1	–0.403
K_{sb} (m/day)	0.30	–0.91	0.0044	–16.8	0.80
K_{sb} (m/day)	30.0	0.09	0.0005	2.55	0.0107
R (cm/year)	1.07	–2.75	0.0553	29.48	–0.509
R (cm/year)	5.05	5.74	0.0553	–39.63	0.415

river leakage, with sensitivity coefficients of 0.687 and 1.37, respectively.

These results are comparable to those of Christenson (1983) who tested variations in K, R, and K_{sb} on a 40-year simulation with multiple pumping wells. He found that variations in K and R caused the computed heads to change significantly, while 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.

Model Simulations

Oklahoma policy specifies a maximum permitted withdrawal as the pumping rate where 50% saturated thickness remains in 20 years. This was evaluated by the procedure used by the OWRB, that is placing one well, screened to the bottom of the aquifer, in every cell (12,500 wells or 100% development) and simulating 20 years of pumping at various rates. The maximum pumping rate is that at which one-half of the cells are depleted to the 1.52 m minimum level (N. Osborn, Oklahoma Water Resources Board, October 2008, personal communication). The model was run for 20 years with 2,433 time steps. Once the maximum permitted pumping rate was determined, we examined the effect at 10, 20, 30, 40, 50, 60, 70, and 80% development. The endpoint of 50% of wells depleted was only used to establish the maximum pumping rate. All subsequent analyses are based on the aquifer saturated thickness and total storage.

In this model each well represented 100 acres (40.5 ha), which is typical for an irrigation well in this part of the state (M. Kizer, Oklahoma State University Irrigation Specialist, February 2009, personal communication). With the total land area overlying the aquifer at 247,097 acres (99,600 ha), 10% aquifer development would equate to 247 wells pumping continuously over a 100-day irrigation period. Well logs from the OWRB were used to place the first 150 wells approximately at their known locations. Remaining wells were assigned randomly until the desired number of wells for each level of aquifer development was obtained. All wells were assumed to be irrigation wells in the model since these constituted the majority of pumping within the aquifer, and even public water system wells follow a two-season cycle. This is consistent with the finding of Zume and Tarhule (2007) that irrigation wells accounted for the majority of stream depletion. Each simulation was run for 20 years with 100 days pumping followed by 265 days nonpumping.

The simulations for Texas Panhandle GCD policy were run with the aquifer 20, 40, 60, and 80% developed. Pumping rate was varied at each level of aquifer development until 50% of the aquifer storage remained after a 50 year simulation. Each simulation was run for 50 years consisting of 100 days pumping followed by 265 days nonpumping.

Results and Discussions

The amount of water that may be pumped from the alluvial aquifer by Oklahoma policy, depleting no more than 50% of wells after 20 years, was found to be 1.03 acre-ft/ac/year (3,139 m^3/ha/year). Therefore, based on this policy and the results of the model, any permittee could pump 1.03 acre-ft of water annually for each acre of land owned or leased. These results correspond to the rate that Christenson (1983) calculated and is currently permitted in the North Canadian Alluvial Aquifer. With each irrigation well representing 100 acres (40.5 ha), the pumping rate for Oklahoma water policy is 1,270 m^3/day per well for 100 day/year. This permitted quantity remains the same indefinitely and need not be revisited. Even if more wells are drilled, each permittee is allowed 1.03 acre-ft/year (1,270 m^3/year) of

Table 3. Initial Storage Remaining After Various Levels of Aquifer Development, Applying Oklahoma, and Texas Rules (1.0 acre-ft/ac = 3,048 m^3/ha).

	Oklahoma Rules		Texas Rules	
Percent of Aquifer Development	Pumping Rate (acre-ft/ac/year)	Percent of Initial Storage	Pumping Rate (acre-ft/ac/year)	Percent of Initial Storage
10	1.03	94	*	*
20	1.03	84	2.0	64
30	1.03	79		
40	1.03	70	2.0	58
50	1.03	61		
60	1.03	55	1.14	50
70	1.03	48		
80	1.03	45	0.5	50

*Odd percentage of development not simulated for Texas rules.

water for each acre (0.4047 ha) of land owned or leased. This water policy is sustainable if demand is small, but as the aquifer becomes more developed, the rate of water table decline and river leakage may become problematic. For example, when development exceeds 65%, more than half of the aquifer storage would be depleted (Table 3), and at 10% development (247 wells) the average drawdown per cell after 20 years would be 0.90 m, increasing to 8.27 m at 80% development.

We analyzed base flow and river leakage in the alluvial system at 10 and 20% aquifer development (247 and 494 pumping wells) based on Oklahoma policy. Aquifer discharge was calculated at every time step in the MODFLOW simulation. The base flow and river leakage were compared after each period (100 days pumping, 265 days no pumping). At 10% development base flow decreased 62% after 5 years of pumping, 77% after 10 years, and 84% after 20 years. River leakage increased 18% after 20 years (Figure 3). The hydraulic gradient reversed and the stream became a losing stream after approximately nine years of pumping as indicated by the arrow in Figure 3. Changes were much more dramatic at 20% aquifer development with base flow virtually gone after 10 years. River leakage increased 255% after 5 years of pumping, 483% after 10 years, and 692% after 20 years (Figure 4). After only three years of pumping the stream loses more water than it gains. Figure 5 shows the hydraulic head after simulation at 10% development. These results are comparable to those of a similar aquifer study in northwestern Oklahoma (Zume and Tarhule, 2007).

Once the river becomes a losing stream, the surface water-groundwater system will behave differently in MODFLOW, as the system goes from hydraulically connected to hydraulically disconnected (Fox and Gordji, 2007; Bruner *et al.*, 2010). Further it is unlikely the upstream reservoir can maintain the hydraulic connection. Thus, groundwater depletion in the vicinity of the channel is probably underestimated. This effect, however, will be local and should not change the conclusions of the study.

Texas Panhandle GCD policy would not limit pumping rate at low development, but we limited it to 2.0 acre-ft/ac/year (6,096 m^3/ha/year), the temporary rate used in Oklahoma for alluvial basins where a study of maximum yield has not been conducted. At higher rates, too many cells went dry. Table 3 shows that although at 20 and 40% development individual permittees could pump whatever they wanted (the rule of capture concept), each well would ultimately be limited to 1.14 acre-ft/ac/year (3,475 m^3/ha/year) and 0.50 acre-ft/ac/year (1,524 m^3/ha/year) at 60 and 80% development to maintain saturated thickness at 50% after 50 years of pumping. Though under current Texas Panhandle GCD policy, unlimited pumping is permitted at first, five year readjustment protects the aquifer.

Conclusions

Groundwater is a resource that each state regulates differently. The aquifer characteristics and water allocation policies determine how water resources will be sustained for future generations. Calculating the quantity of water moving between a stream and its alluvial aquifer is challenging due to variability in weather and climate and heterogeneity in the aquifer. Sensitivity analysis showed that aquifer conductivity (K) and recharge rate (R) are the most critical parameters in modeling this process, suggesting that money and effort should focus on estimating these parameters. On the other hand, a reasonable estimate of streambed hydraulic conductivity (K_{sb}) and specific yield (S_y) should be adequate for long-term analysis of interchange of water between the stream and alluvial groundwater.

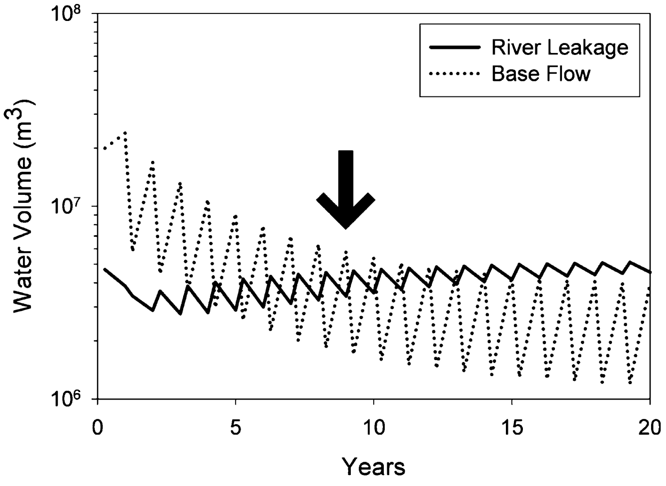

Figure 3. Total Base Flow and River Leakage After a 20-Year Simulation at 10% Aquifer Development.

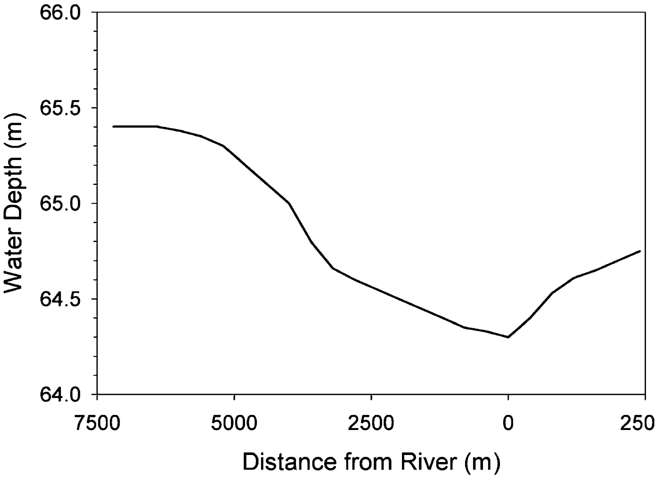

Figure 5. Hydraulic Head Perpendicular to the River, Midway Between Canton Lake and Lake Overholser After 20 Years of Simulation at 10% Development. The river has the lowest elevation head.

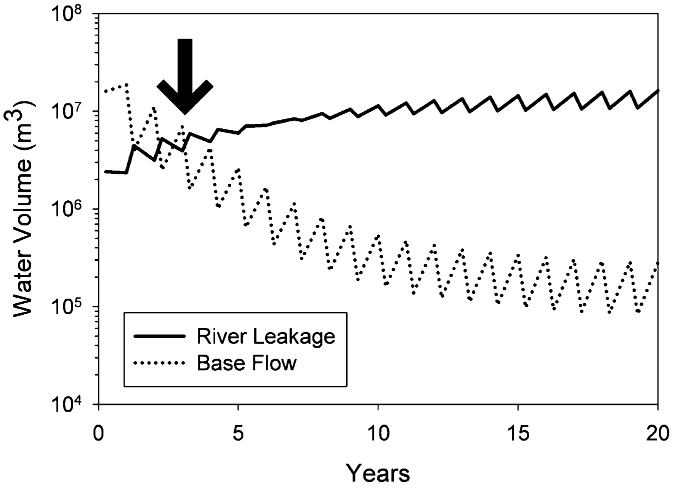

Figure 4. Total Base Flow and River Leakage After a 20-Year Simulation at 20% Aquifer Development.

Though several states recognize the interaction between surface and groundwater, Oklahoma and Texas do not. The current groundwater law that Oklahoma has implemented allows efficient utilization of the aquifer with only a slow decline of water table while development is low; however, there is no provision to revise permits as more wells are pumped. This may cause significant local drawdown of the water table, eventually depleting the resource. On the other hand, the rules of the Texas 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 total storage in the aquifer, but also to consider the interchange between the aquifer and the river (base flow and recharge) and to retain flexibility to readjust permits if development exceeds the original assumptions. The North Canadian Alluvial Aquifer, which currently has approximately 150 irrigation wells and a smaller number of municipal wells, is approximately 6% developed. The model shows that as the number of wells increases, base flow will decline and river leakage will increase. At 20% development (about 500 wells) river flow will essentially cease within three years of pumping. As the demand increases within the basin, the pumping rate should be revisited and readjusted accordingly.

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