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MODELING THE RESPONSE OF A SHALLOW ALLUVIAL AQUIFER TO IMPACTS OF CLIMATE VARIABILITY AND ANTHROPOGENIC WATER WITHDRAWAL IN NORTHWESTERN OKLAHOMA

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In partial fulfillment of the requirements for the

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A DISSERTATION APPROVED FOR THE
DEPARTMENT OF GEOGRAPHY

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Abstract

Alluvial aquifers are the most reliable sources of water for human consumptive uses and for sustaining riparian ecosystems in semiarid environments. Regardless, very little is known about their dynamics relative to bedrock aquifers. For example, it is not entirely clear how alluvial aquifers respond to impacts of climate variability and change. Similarly, the question about how pumping these aquifers impact stream-aquifer interactions has not been fully explored. This dissertation explores the dynamics within the alluvium and terrace (A&T) aquifer of the Beaver-North Canadian River (BNCR) in semiarid northwestern Oklahoma. The study includes three self-contained but related studies; (1) an analysis of northwestern Oklahoma precipitation and streamflow time-series for trends and periodicities; (2) an investigation of the impacts of groundwater pumping on stream-aquifer interactions within the alluvial basin, and (3) a numerical simulation of the response of the alluvial aquifer to various scenarios of climate variability and anthropogenic groundwater pumping. The numerical simulation is accomplished using a three-dimensional groundwater flow model, MODFLOW.

Broadly, results of this study indicate that the combined impacts of anthropogenic pumping and climate variability will create drawdown of greater than 12 m in the alluvial aquifer. Spatially however, areas of high drawdown will be localized, driven primarily by the intensity of pumping from well clusters. The worst impacts both from anthropogenic and climatic stresses will be on stream-aquifer interactions. Anthropogenic pumping for example, depletes streamflow by intercepting baseflow to streams, while, at the same time, inducing higher leakage from the streams into the aquifer. Climate, on the other hand, controls the amount of recharge to the stream-aquifer system. Thus, by simulating

various anthropogenic and climatic stress scenarios on the study aquifer, this research provides information that can be used for evaluating competing aquifer management options.

Chapter 1

The Research

1.1 Introduction

Semiarid environments are semiarid because they lack adequate water resources. Furthermore, what water does exist in the form of precipitation, surface or groundwater is highly variable over space and time. However, alluvial aquifers are an exception to this general characterization because historically they have been the most dependable sources of water for human consumptive uses and for supporting riparian biodiversity (Linn et al 2003; Lioubimtseva, 2004; Simmers, 2003). As a result, in some semi-arid environments, such as the African Sahel savanna, Brazilian nordeste, India, and China, where water management systems are poorly developed, communities frequently are clustered within alluvial basins because their shallow groundwater systems are reliable, easy to exploit, and provide remarkable defense against recurrent droughts (Cater and Alkali, 1996; Tarhule and Woo, 1997; 2002, Bronstert et al, 2000; Döll and Hauschild, 2002; Guo and Wang, 2004; Cui and Shau, 2005). The situation on the Southern Great Plains of the United States is somewhat different because people do not depend so strongly and directly on unmanaged sources of water. Regardless, alluvial aquifers have unique advantages; studies (e.g. Ryder, 1996)have shown that some alluvial aquifers have higher water yields than adjacent bedrock aquifers but cost considerably less to exploit. As a result, alluvial aquifers are exploited extensively for irrigation, and have contributed to making the Southern Plains one of the most agriculturally productive regions of the United States (Rosenzweig and Reibsame, 1989; Adams and Bergman 1996; OWRB 1997).

Despite their importance, the dynamics of alluvial aquifers are still largely unexplored relative to bedrock aquifers. For example, a large number of studies have investigated human- and or climate change impacts on bedrock aquifers (e.g. Chen et al., 2001; Abderrahman and Rasheeduddin, 1994; Holman, 2006; Alderwish and Al-Eryani, 1999; Rosenberg et al., 1999; Brouyère et al., 2004). In Belgium for example, Brouyère et al. (2004), found that climate change would decrease groundwater recharge, water levels, and thus storage, in a chalky aquifer. Similarly, Loáciga et al. (2000) showed that climate change would decrease flow in springs within the Edwards Balcones Fault Zone aquifer in Texas, and even cause some springs to dry up completely. Chen et al. (2001) investigated the possible effects of climate change on regional water demand and supply as well as on the economy of San Antonio, Texas, which depends on the Edwards aquifer. They report that climate change would reduce aquifer yields but increase water demand such that a regional welfare loss of $2.2-$6.8 million per year may occur.

In contrast, few studies have focused on the dynamics of alluvial aquifers in semiarid regions. Notable among those are Stromberg et al. (1996), who investigated the impacts of anthropogenic groundwater withdrawals on riparian ecosystem in the San Pedro alluvial basin. They found that groundwater level declines of a few meters (0 – 4 m), resulted in a sharp reduction of riparian flora. In the context of climate variability and change, Ngounou et al. (2005) reported declining groundwater levels and surface flows in the alluvial aquifer system of the Logone-Chari river system in West Africa. However, the study was based only on historical data with no projections made into possible future trends.

Elsewhere, studies have shown that excessive pumping can negatively impact alluvial aquifer – surface stream relations (Chen and chen 2004; Nyholm et al. 2002; Osman and Bruen 2002; Wilson 1993). This happens because pumping intercepts groundwater flow that would otherwise end up in the stream as baseflow, and/or, induces higher stream seepage to the aquifer. The combined effects lead to streamflow depletion and can cause a stream that originally was gaining (affluent) to become a losing (effluent) stream. The resulting diminished flow downstream sometimes becomes a cause for conflict among competing users and stakeholders (see, Tarhule and Woo 1997). These anthropogenic effects pose significant threat for alluvial aquifer management.

Climate variability complicates this situation further. The recently heightened interest in climate change-impact assessments derives from evidence suggesting that the world's climate is changing, and that the change will likely continue into the next several decades (IPCC, 2001, 2007). For example, the newly released Fourth Assessment Report (FAR) of the Intergovernmental Panel on Climate Change (IPCC, 2007) projects a global temperature increase of about 0.2^{o}C per decade over the next two decades. Such warmer climate will have a direct consequence on some hydrologic systems by altering established regimes, magnitude, and timing of precipitation (IPCC, 2007; Gleick, 2000; Loáiciga, 2003). For groundwater systems, changes in precipitation inputs may alter recharge dynamics with varying implications both on groundwater quantity and quality (IPCC, 2001; Mabbut, 1989). For semiarid world regions, where droughts are already frequent, a warmer climate is anticipated to enhance drought occurrence, intensity, and persistence depending on the region (IPCC, 2001; Seckler et al., 1999; Mabbut, 1989). Diminished precipitation and more frequent droughts will have adverse consequences for recharge to alluvial aquifers (see Scanlon et al., 2006), and further compound the water issues already faced in many semiarid environments.

The above discussion suggests the need to explore alluvial aquifer dynamics both in the context of anthropogenic demand and climate variability/change. This goal is important for three reasons. First, from an academic perspective, it contributes to the sparse literature on alluvial aquifers generally and so adds to our understanding of their possible response to a combination of stress factors. Second, it contributes to the on-going public and academic discourse on how to translate the possible impacts of climate change into measurable sectoral indicators, in this case water resources (e. g. Don et al, 2005; Ojima et al, 1999; Parson et al, 2003; Xu, 1999; Varis et al, 2004). Third, and finally, an understanding of these dynamics can facilitate policy-making that ensures the rational and sustainable development and management of alluvial aquifers in semiarid environments.

In this dissertation, a three-dimensional numerical groundwater model of the "Alluvium and Terrace" (A&T) aquifer along the Beaver-North Canadian River in semiarid northwestern Oklahoma is developed using the U.S. Geological Survey (USGS) finite-difference groundwater flow model, MODFLOW (McDonald and Harbaugh, 1988). This model is used to evaluate the response of the shallow alluvial aquifer to potential impacts of climate variability and anthropogenic groundwater withdrawals. Additionally, the impacts of both the climate variability and the groundwater pumping stresses on stream-aquifer interaction are investigated. The overarching goal of the study is to provide information necessary for evaluating aquifer management options, including conjunctive water use strategies.

1.2 Problem Statement

The A&T aquifer in northwestern Oklahoma is of great regional importance hydrologically, because it provides nearly 98% of all water needs for the region (OWRB infomix database). Additionally, it is the primary source of non-flood flow for the Beaver-North Canadian River and its tributaries, as well as a critical source for various aquatic and wetland biodiversity.

Northwestern Oklahoma faces a potential dilemma. Global Circulation Models (GCMs) indicate the region is likely to experience future precipitation decreases of up to 25% due to climate variability and change (USGCRP, 2000). Yet, the region's water demand is projected to increase 53% by 2050 (OWRB, 1997), creating a yawning gap between supply and demand. These dynamics can be expected to impact regional groundwater and streamflow but the questions of how these impacts may manifest, and to what degree, has not been investigated systematically. An exception is the study by Davis and Christensen (1981), which investigated the impacts of aquifer pumping on groundwater levels in the A&T aquifer using a 2-dimensional numerical groundwater model. The study projected that stressing the aquifer from 1978 to 2020 at the 1977 pumping rates and abstraction points would decrease its saturated thickness only by an average of 0.5 m. The Davis and Christensen's study is important for two main reasons. First, it established important hydrological links and provided information on key processes and factors that constitute baseline values for contemporary research. Second, it pioneered efforts to document and determine the impacts of anthropogenic use on groundwater resources in northwestern Oklahoma. Despite those contributions, a number of technological advancements have occurred in the period since Davis and Christensen completed their study that brings to the fore some limitations in their approach. First, the model was two-dimensional, and therefore assumed that flow in the aquifer is entirely horizontal. It is important to acknowledge that this limitation was a sign of the times, i.e. limitations in computing capabilities seriously constrained implementation of 3-D models at the time. Nevertheless, the fact remains that 2-D models do not adequately represent the physical system which is 3-dimensional. With specific respect to alluvial aquifers for example, the vertical flow field induced in the vicinity of partially-penetrating streams and pumping wells is too important to be ignored (Bear and Verruijt, 1987). Second, it did not consider the impacts of climate variability on the aquifer. Third, it did not explore fully the broader implication of aquifer pumping on stream-aquifer interaction. Fourth and finally, the hydroclimatic and water use dynamics have changed considerably since the study was completed nearly three decades ago. For example, the number of pumping wells in the aquifer has nearly doubled since the 1970s, and so have the volumes of water withdrawal (OWRB database). The present study takes advantage of enhancements in 3-D modeling capabilities to simultaneously investigate the impacts of both climate variability and anthropogenic water use on the A&T aquifer. Additionally, it investigates in great detail the interaction between the alluvial aquifer and the overlying streams.

1.3 Objectives

The specific objectives of this dissertation are to:

(i) Investigate the nature and historical patterns of hydroclimatic variability in northwestern Oklahoma;

(ii) Develop a 3-dimensional groundwater flow model of the A&T aquifer in northwestern Oklahoma;

(iii) Use the model developed in (ii) above to evaluate the response of the A&T aquifer to various scenarios of anthropogenic water use and climatic variability.

(iv) Investigate the dynamics of the interactions between the A&T aquifer and the overlying BNC River system.

(v) Provide information that facilitates decision-making regarding the rational and sustainable development and management of the A&T aquifer.

1.4 Organization of the Dissertation

This dissertation is organized into six chapters. The current chapter (1) introduces the study, laying out the foundation and the problems investigated by the study. Chapter 2 describes the basic climate, physiographic features, geology, and hydrology of the study area as well as the basic concepts of groundwater modeling. Furthermore, it outlines the conceptual framework for developing the aquifer model and provides a detailed description of the computer code used. In chapter 3, an in-depth analysis of precipitation and streamflow time series for the study area is presented (i.e. Objective 1). Chapter 4 discusses the simulation of stream-aquifer interactions resulting from anthropogenic groundwater withdrawal (Objectives II & IV), while chapter 5 presents simulation results of the combined climatic and anthropogenic stress-scenarios on the aquifer (Objectives II, & III). The final chapter (chapter 6) summarizes the major findings and provides some conclusions (Objective V).

Chapters 3 through 5 are written to be stand-alone technical papers, formatted according to specific journal styles. Because of this structure, each of these chapters features a separate introduction, abstract, methodology, discussion and conclusions. As a result some repetition is unavoidable. In particular, key background information, such as location map, site-specific information, and references were repeated in order to achieve the desired chapter autonomy. The status of each stand-alone technical manuscript (chapters 3 through 5) is shown below:

Chapter 3 - "Precipitation and streamflow variability in northwestern Oklahoma" - published in *Physical Geography* 2006*,* 27 (3), p189-205.

Chapter 4 - "Simulating the effects of well pumping on groundwater levels and streamflow in northwestern Oklahoma"- Accepted, *Hydrogeology Journal.*

Chapter 5 - "Alluvial aquifer response to climate variability and groundwater exploitation on the united states southern great plains"- submitted to, *Water Resources Management*.

1.5 Research Contribution

On a broader scale, this research fills a critical gap regarding the understanding of alluvial aquifer dynamics in semiarid locations, particularly, how they respond to impacts of climatic variability and anthropogenic exploitation patterns. By utilizing a numerical groundwater flow model, which offers predictive capabilities, this study provides a proactive approach to evaluating competing management options for shallow aquifers on the basis of insights gained from simulating several stress scenarios.

This study also explicitly evaluates stream-aquifer interaction both at the reach and stream segment scales, which permit identification of local, fine-scale heterogeneities.

For northwestern Oklahoma, whose economy depends heavily on irrigated agriculture with the bulk of the irrigation water supplied by the study aquifer, results of this study can inform agricultural planning strategies that take into account projected impacts of external stresses on the A&T aquifer, the most important regional source. Finally, the study can be replicated in other basins within Oklahoma and beyond to inform decision making regarding water resources, planning, exploitation, and management.

1.6 Limitations of the Study

Numerical groundwater modeling has some limitations that must be noted by any modeler or user. First, it is based on several assumptions about the physical hydrogeologic system being modeled, some of which may be only approximately correct. For example, the finite-difference approach used in solving the groundwater flow equation in this study places the model solution at the center of each grid cell under the assumption that material properties are homogenous or vary linearly within the cell. In reality however, the distribution of aquifer parameters may vary significantly within a grid cell, depending on the size of the grid. For purposes of this study however, this limitation is not considered critical because the stress impacts of interest are on the regional rather than the local scale. Closely related to the above limitation is the inability to fully distribute model parameters (e.g. hydraulic conductivity and recharge) over the model domain. This is because the actual field distribution of these parameters is never known.

Another limitation lies in the definition of stress periods in the model, especially in the predictive phase. Most model inputs, including pumping and boundary conditions are assumed constant for a given stress period. In reality however, stresses can change over short times given the dynamic nature of factors (both anthropogenic and natural) influencing groundwater dynamics. Keeping stresses constant nonetheless is the best approximation since there is no better way of forecasting these conditions on a finer scale. Other sources of error are embedded in the various data used. In this study, for example, difficulties were encountered in allocating reported withdrawals to specific wells as required by the modeling code. This is because most groundwater wells are not metered and therefore permit holders report use per permit rather than by individual wells. The problem is that one permit may apply to several wells. In this study therefore, reported water withdrawals were divided equally among all wells under the applicable permit. This approach may underestimate or overestimate withdrawal rates at some wells in a manner that ideally cancels out but there is no way of determining this for certain. . For this study specifically, another possible source of withdrawal underestimation may be in the hundreds of domestic and stock wells whose withdrawals are not reported because Oklahoma groundwater law does not require permitting for these categories of wells. This situation also may underestimate the magnitude of impacts assessed but again, there is no way of knowing for sure.

Finally, the numerical solution itself is an approximation in that it replaces the theoretical differential equations governing groundwater flow with systems of algebraic equations whose solution can never be exact. Despite these limitations, a groundwater model is still the best available decision-making tool for evaluating groundwater development and management options (Reilly, 2001).

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Chapter 2

Background

2.1 The Study Location, Physiography and Climate

Throughout the length of the Beaver-North Canadian River (BNCR) across Oklahoma, Quaternary alluvium and terrace deposits occur, and constitute a very productive aquifer system (OWRB, 1990). Figure 2.1 locates the portion of the system studied in this dissertation, which is the 2150 km^2 area from the Beaver/Harper County boundary line down to Lake Canton in Blaine County. In this study, the aquifer is referred to as the Alluvium and Terrace (A&T) aquifer of the Beaver-North Canadian River (BNCR) in northwestern Oklahoma. The A&T aquifer is one of the most important shallow groundwater basins in the state of Oklahoma (OWRB, 1990). The state of Oklahoma defines a groundwater basin as an area whose geologic units have an average saturated thickness of, at least, 1.5 m (Davis and Christenson, 1981).

The A&T aquifer is located within the Western Sand-Dune belt geomorphic province of northwestern Oklahoma generally characterized by hummocky dunes and sandhills, which are stabilized by vegetation (Johnson et al., 1972; Woods and Stacey, 1965). The surface elevation (altitude) slopes from about 701 m above sea level (m.a.s.l) in the northwest corner to about 488 m.a.s.l in the southeast part of the study area. Local relief however, is generally less than 30 m (Davis and Christenson, 1981). Soils of the study area do not vary much, both within the alluvium and the terraces. Major soil types include the Tivoli-Pratt-Ottero, the Lincoln-Yahola, the Lincoln-Sweetwater, and the Lincoln-Las Animas associations. These are predominantly deep, dunned sands that are well-drained with fair amount of loam (U.S. Dept. of Agriculture, 1960a and b, 1968).

The climate of the study area is largely semiarid although the lower southeastern part is characterized by a dry, sub-humid climate. Data on regional climatic variables, including precipitation, temperature, and snowfall, are contained in the National Weather service Cooperative Observer network (COOP). Time-series data at several gauging stations date back to the late 1800s (refer to Figure 2.1 for the distribution of the COOP network rain gauges as well as the USGS stream gages within and around the study area). The time-series data were used to compute the area climatology discussed here and to perform the climatic analyses presented in chapter three. Area precipitation occurs frequently as rainfall but some snow or sleet is recorded in the winter with nearly every year recording, on average, at least, 254 mm of snow (Oklahoma Climatological Survey; www.ocs.edu). Average annual precipitation ranges from approximately 565 mm in the northwestern part of the area to approximately 775 mm in the southeast. Year round, 83% of the precipitation falls between the months of March and October. May and June however, receive the highest amounts (16% and 13% respectively) of the total precipitation. Figure Fig. 2.2 shows the average monthly and annual precipitation over the study area for the period 1971-2003. Year-to-year precipitation variability for the entire area is high with a coefficient of variability of about 19%.

Annual evaporative losses from surface drainage network in the area range from 1422 mm to 1626 mm, on average, about 230% of annual precipitation (OWRB 1997). The high evaporative rates and the intermittent periods of less than normal precipitation make the study area prone to water shortages.

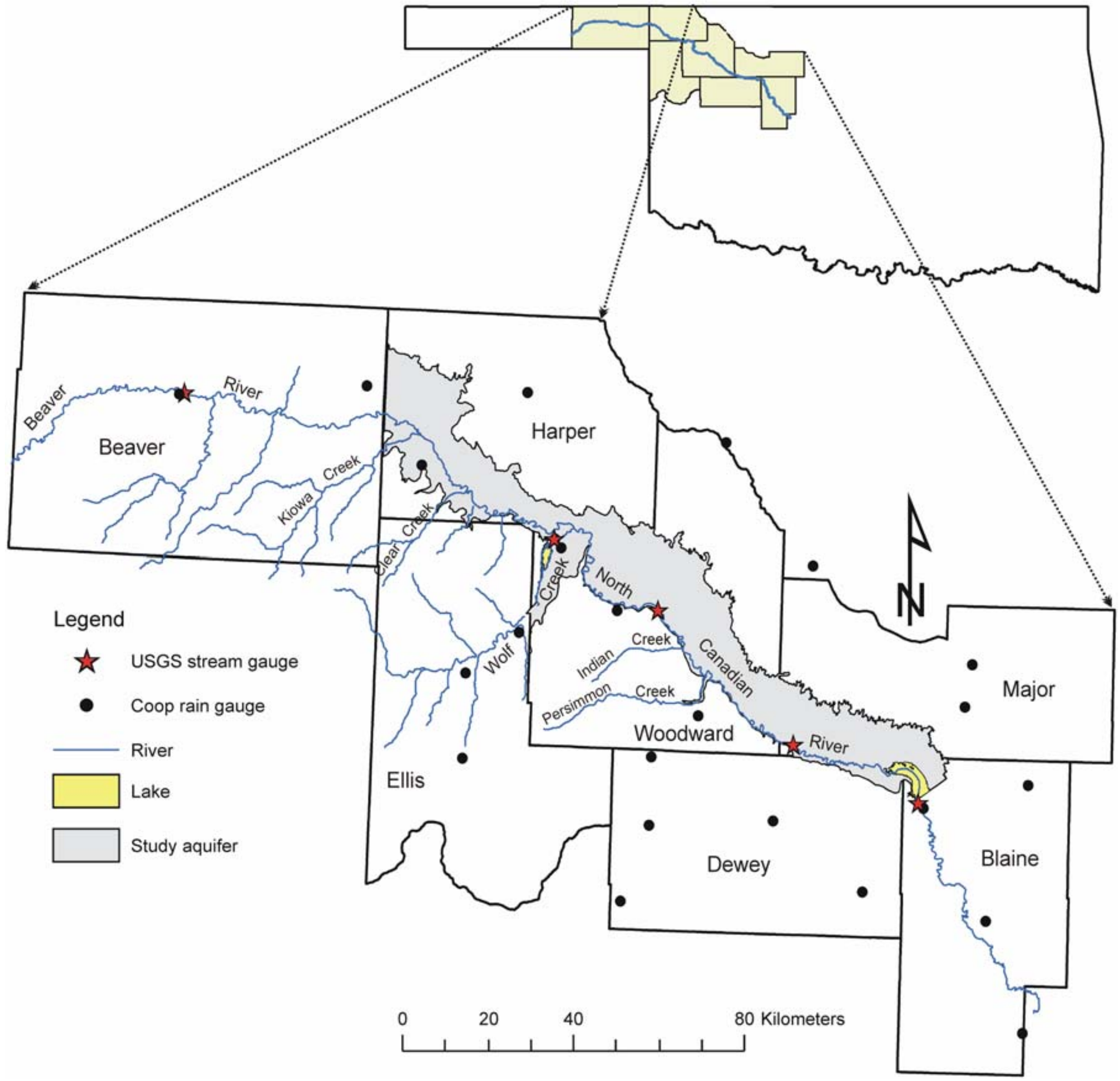

Figure 2.1: Study location map showing also, the drainge network, COOP precipitation gauging stations, and USGS streamflow gauges.

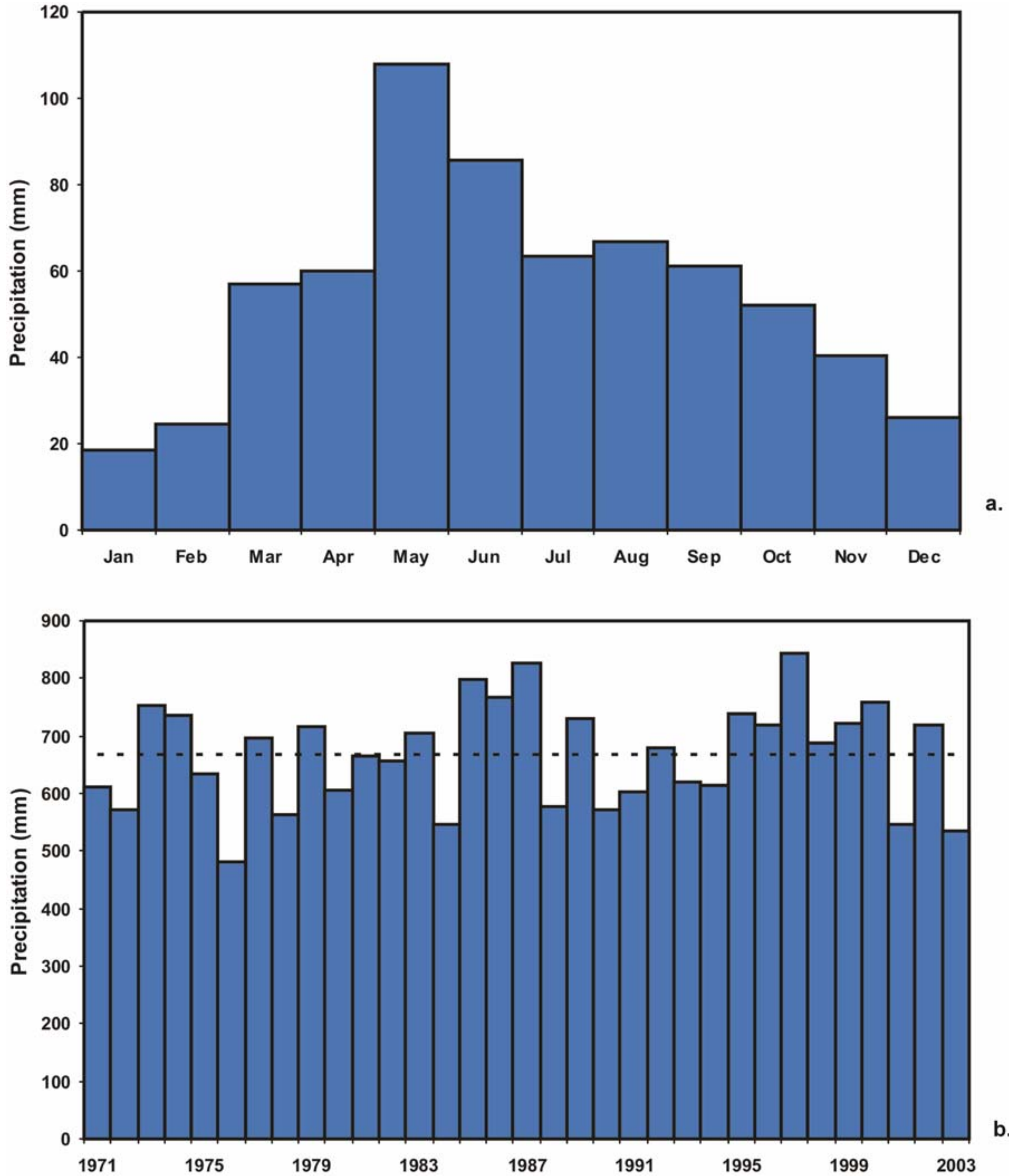

Figure 2.2: Study area (a) average monthly precipitation (1971-2003), (b) total annual precipitation. Dotted line is the long-term average

Temperatures over the area average near 16^0 C with a slight increase from north to south. Daytime temperatures in the northern part range from an average high of 37^0 C in July to an average low of -6^0 C in January. For the southern part, average daytime high of 34^0 C occurs in July and a low of $-3.3\ ^0$ C in January (Oklahoma Climatological Survey; www.ocs.edu).

2.2 Land use/Land cover

Table 2.1 shows the generalized land cover and land use classification for areas within the study watershed (the BNCR). The data presented in the table were derived from the Oklahoma Natural Resources Conservation Service's (NRCS) MIADS land use/land cover (LULC) data (www.ok.nrcs.usda.gov/technical/gis.html). The NRCS LULC dataset is grouped by county or by 11-digit hydrologic unit. The hydrologic unit data is more detailed because it further breaks each county data into watersheds, which makes it easier to delineate specific areas of interest. The study aquifer falls within the Middle North Canadian watershed, and is represented by three of the NRCS' 11-digit hydrologic units; Moreland Laterals, Bent Creek, and permission Creek. To obtain area-wide information, the LULC data for these three hydrologic units were redistributed to compute the percentages shown in Table 2.1.

As table 2.1 shows, the study watershed (the BNCR) is predominated by rangeland, mostly open grasslands sand sage. Cropland constitutes nearly 30% of the area, with a significant portion irrigated. Among the major crops grown in the area are wheat, sorghum, oats, rye, corn, and hay, but wheat is by far the most planted crop in the area. Other crops like peanuts and barley are restricted to one or two counties. Industrial land use is mostly for oil and gas and related service companies. Major livestock operations are for cattle, hog, pigs, sheep, horses, and quail.

2.3 Geology

The A&T aquifer is underlain by Quaternary-age alluvium and terrace deposits. These deposits are made up of poorly sorted, fine to coarse, unconsolidated quartz sand with minor amounts of clay, silt, and basal gravel (Davis and Christenson, 1981). The deposits occur mainly north of the Beaver-North Canadian River and spatially extend about 1.7 – 24 km from the river banks. This predominantly northerly location is most likely the result of the river's southerly migration down the regional dip of the underlying red beds formation and the influence of dominant southerly winds.

The Quaternary deposits are composed of four distinct units—the high and low terrace deposits, the alluvium, and dune sands. Terraces represent older and higher stages of the depositing river. The high terrace deposits occur farthest from the river channel and have an average thickness of about 21 m. These deposits are of Pleistocene age and are believed to have been derived by the reworking of the Ogallala and the adjacent Permian formations (Davis and Christenson, 1981). Next to the high terrace deposits and closer to the river channel are the Pleistocene-age low terrace deposits. These occur along both sides of area streams and average a thickness of about 15 m. The stream channels and their floodplains are composed of alluvial deposits, which are of Holocene age. The alluvial deposits average a thickness of about 9 m. Dune sands, which are derived from the underlying terrace and alluvium deposits, overlie the later for most of the area.

Table 2.1: Generalized land use and land cover classification for the study area.

Generalized Class	Percent
Cropland	29.53
Cropland – Irrigated	1.28
Rangeland - Open grasslands	24.46
Rangeland – Sand sage; Low density – Canopy < 15%	3.43
Rangeland – Sand sage; High density – Canopy > 15%	18.75
Rangeland – Shinnery Oak; Low density – Canopy < 15%	1.01
Rangeland – Shinnery Oak; High density – Canopy > 15%	3.70
Rangeland – Juniper/Red Cedar; Low density - < 100 Plants/ac	1.52
Rangeland – Juniper/Red Cedar; High density - > 100 Plants/ac	0.38
Rangeland – Postoak/Blackjack; Low density – Canopy < 35%	1.52
Rangeland – Postoak/Blackjack; High density – Canopy > 35%	2.77
Rangeland – Cottonwood/Elm/Hackberry; Low density < 20%	1.69
Rangeland – Cottonwood/Elm/Hackberry; High density > 20%	2.33
Rangeland – Salt Cedar/Baccharis; Low density – Canopy < 10%	0.04
Rangeland – Persimmon/Summac; Low density - < 25	0.01
Pastureland	3.33
Pastureland – Irrigated	0.16
Woodland – Windbreaks and Cropland	0.05
Woodland – Windbreaks and rangeland	0.02
Wetland – Forested	0.02
Urban Ranchette – House and Lot/Tract (2 to 20 acres)	0.18
Farmstead (Greater than 5 acres)	0.28
Oil – Waste land	0.01
Quarries and Gravel pits; > 5 acres	0.01
Confined feeding operation	0.02
Conservation Reserve Program – Grass	0.18
Water/Bare Sand channel (rivers)	0.45
Urban built-up land	1.71
Water (Lakes/Ponds)	1.17
Total	100.00

Thicknesses of these dunes vary from place to place but reach a maximum height of about 6 m. The dune sands are generally unsaturated but greatly facilitate recharge to the aquifer (Woods and Stacey, 1965).

For most of the study area, the Quaternary deposits unconformably overlie the eroded surface of the Permian Red Beds and the Tertiary Ogallala formation. The Red Beds are of the Whitehorse group, which includes the Rush Springs sandstone and the Marlow formation. These formations are composed primarily of fine-grained, red sandstone, siltstone, shale, gypsum and dolomite. The bedrock surface of the Whitehorse group is an erosional unconformity having a topographic relief of several hundred meters (Wood and Stacey, 1965). Figure 2.3 shows the geology of the study area.

2.4 Hydrology

A fair understanding of the occurrence and movement of surface water and groundwater in a basin, as well as their interaction, is required to develop a good conceptual model for simulating aquifer dynamics. This section describes the surface and groundwater hydrology of the study area. This discussion will set the stage for the model assumptions, boundary conditions, and inputs used to implement the numerical groundwater model developed in this study. Although no clear physical boundaries exist between groundwater and surface water, for clarity and ease of presentation, the two systems are discussed separately.

2.4.1 Surface Water

Major rivers draining the study area are the Beaver and the North Canadian Rivers. Each of these rivers has a few tributaries that drain adjoining areas into them (refer to Figure 2.1). The Beaver River is a perennial river that enters Oklahoma through the southwestern part of Cimarron County from New Mexico. From Cimarron County, the river loops south and flows for about 19 km in the state of Texas before re-entering Oklahoma in Texas County. The Beaver River enters the study area through an eastward path across Beaver County and then flows southeasterly, becoming the headwaters of the North Canadian River in Woodward County. Near the city of Fort Supply, Wolf Creek

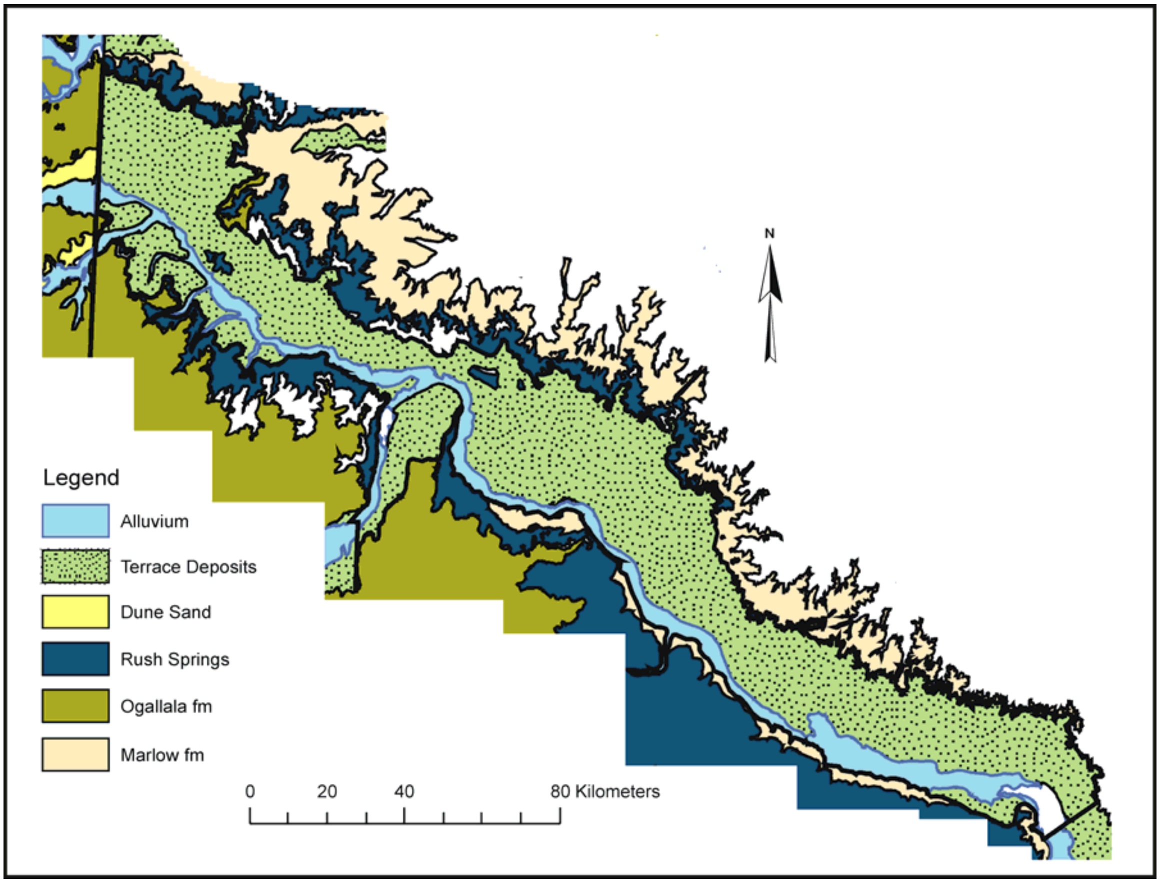

Figure 2.3: Map showing geology of the A&T aquifer.

flows into the Beaver. It is from this confluence of the Beaver/Wolf Creek downwards that the Beaver River becomes known as the North Canadian River. The North Canadian continues its southeasterly migration across central Oklahoma before joining the Canadian River to empty into the Arkansas River to the east. Within the study limits, Davis and Christenson (1981), coined the term “Beaver-North Canadian River” to refer to the combined channels of the Beaver and the North Canadian Rivers. The same term is adopted in this dissertation. Some of the major tributaries of the BNCR within the study area are the Kiowa, Clear, Wolf, Indian, and the Persimmon Creeks. All these creeks drain the area underlain by the Permian and Tertiary formations south of the major rivers. There are no tributary streams that drain the study area to the north. Most of these tributaries are intermittent.

Flow in the BNCR system is monitored through a network of U.S. Geological Survey (USGS) streamflow gauges. Four USGS gauges are located within the study limits (refer to Figure 2.1); USGS 07237500, 07238000, 07239000, are on the North-Canadian River at Woodward, Seiling, and Canton respectively, while USGS 07237800 is on the Wolf Creek.

In addition to the surface stream network described above, two reservoirs are located within the BNCR basin. Fort Supply Lake is located at the mouth of Wolf Creek near the city of Fort Supply in Woodward County. Further downstream on the North Canadian River, Lake Canton is located near the city of Canton in Blain County.

2.4.2 Groundwater

Groundwater in the A&T aquifer occurs in the alluvium and terrace deposits, which are hydraulically connected to form a single aquifer. Although numerous clay layers occur at several localized positions within the aquifer, none is regionally expansive so that the aquifer is regionally unconfined (Davis and Christenson, 1981). The saturated thickness of the aquifer varies from a few meters to more than 20 m at areas having high thicknesses of the terrace deposits. For an unconfined aquifer, the saturated thickness at a point is determined by subtracting the elevation of the base of aquifer from the elevation of the water table. For the study aquifer a water table elevation map was produced based on 1978/79 water level measurements in several observation wells across the aquifer (Figure 2. 4a). This period was chosen to represent the predevelopment conditions in the aquifer (e.g. Davis and Christenson, 1981) for model calibration purposes. Similarly, the general configuration of the base of the aquifer was obtained by contouring depths to the red beds formation at 400 discrete wells across the aquifer (Figure 2.4b). The two maps provided the spatial picture of the aquifer's saturated thickness.

The aquifer is confined underneath at most locations by the Permian Red Beds. Drillers' logs for wells completed in the aquifer, provided by the Oklahoma Water Resources board (OWRB) (also online at www.owrb.ok.gov/wd/search/search.php) indicate the base of the aquifer at most locations is the top of the red beds. The Red Beds formation is relatively impermeable at most places and act as a barrier to vertical flow from the A&T aquifer.

Recharge to the aquifer is primarily from precipitation but influent seepages from overlying streams and adjacent groundwater basins also contribute a significant component of the recharge (OWRB, 1997). For example, lateral underflow from the Ogallala formation helps to replenish the aquifer (Davis and Christenson, 1981). Simulation results from this study estimate the Ogallala inflow to be 1,578 m^3/day.

The rate of groundwater movement in the aquifer is governed by the hydraulic properties, notably, the hydraulic conductivity (K), which is the parameter describing the rate at which water can move through a porous medium, the hydraulic gradients, and the storage coefficient. Under water table conditions the storage coefficient is equal to the specific yield (S_y). K for the aquifer was determined from model calibration to range between 0.78 – 65 m^3/day, with an average of 30.8 m^3/day. The specific yield was determined to be 0.28, consistent to Davis and Christenson's (1981) value of 0.29. The water table map in Figure 2.4a shows that the hydraulic heads in the aquifer are higher for topographically higher areas (on the high terraces) and lower close the river channels. Thus, the general groundwater flow direction is southwesterly toward the BNCR. A few exceptions to this generality occur in some areas where the contours suggest leakage from the aquifer to adjacent formations occurs. For example, in the area around the northwestern part of Harper County, isolines suggest lateral leakage from the aquifer into adjacent formations.

2.5 Anthropogenic Water Use

The A&T aquifer is the most important source of water for irrigation, municipal supply, power supply, agriculture, and industrial uses in northwestern Oklahoma. Groundwater is withdrawn from more than a thousand wells distributed all over the aquifer. However, the majority of these wells are domestic and stock wells extracting less than 17 m^3/d (5 acre-feet per year). By Oklahoma groundwater law, groundwater use for domestic and stock purposes extracting less than 17 m^3/d of groundwater requires no permitting (Noel Osborn-OWRB, pers. Comm.). Thus, there is no way of accounting for the amount of water withdrawn for these purposes even though the combined total per year may be significant. Also not directly accounted for is the groundwater that discharges from the aquifer as springflow, such as at the Boiling springs in Woodward County. For any other purpose that requires more than 17 m^3/d, the OWRB must issue a

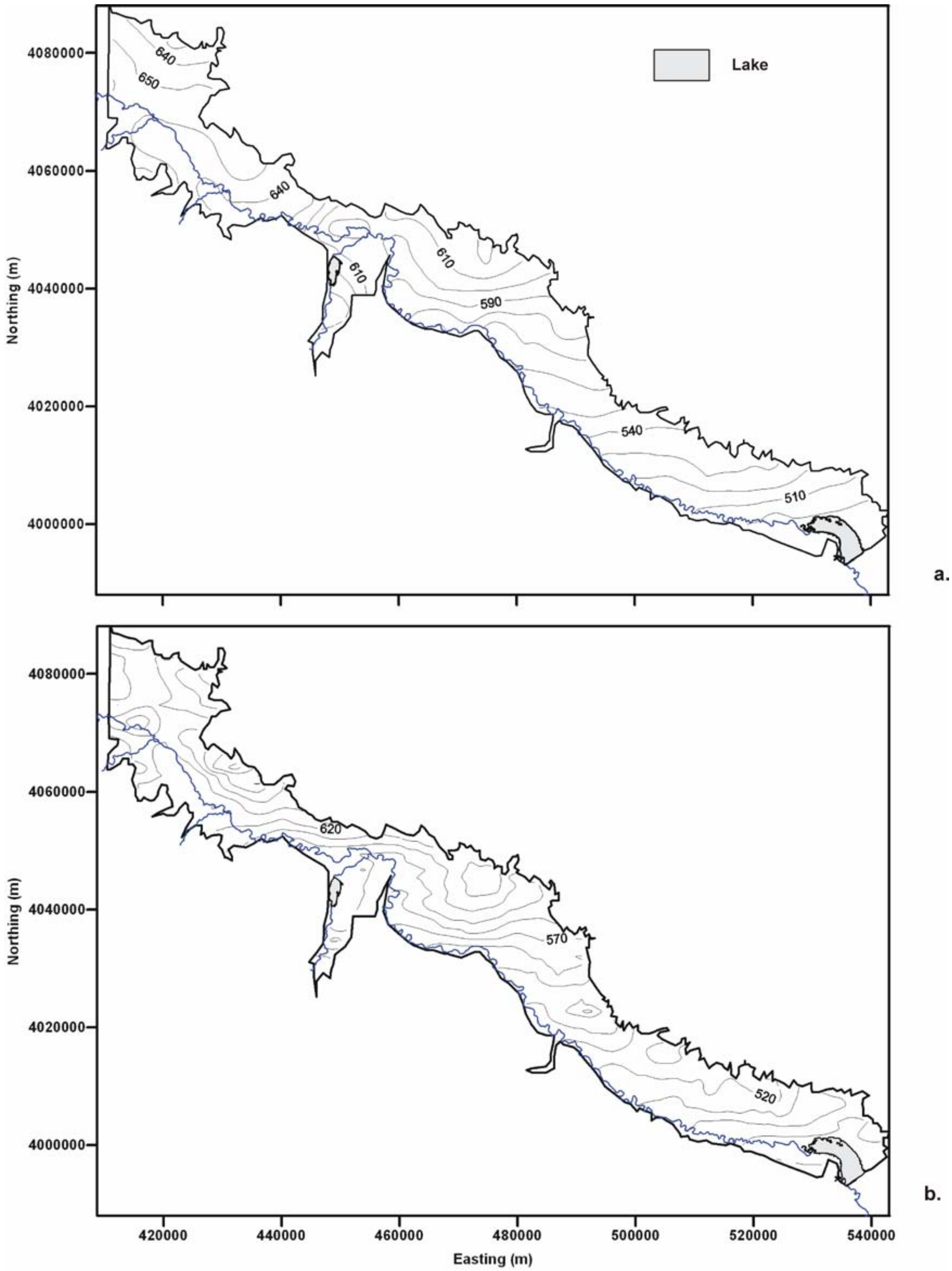

Figure 2.4: (a) Water table map of the A&T aquifer during 1978/79, (b) configuration of the base of aquifer.

permit, which also mandates the permit holder to report his/her use annually. In this way, the OWRB maintains a database on water withdrawal from the aquifer. The withdrawal data used for this research was supplied by the OWRB.

Evaluation of the OWRB water allocation data for the study area indicates that 97.5% of total allocation is for groundwater. Of this 68% is allocated to irrigation use, 25% to municipal water supply, and 6% to power supply. The remaining 1% is shared among agriculture, industrial, recreation and other commercial uses. Only 2.5% of the total water allocation comes from diversions of the Beaver-North Canadian River. Such diversions also are mostly used for irrigation. Note that the above statistics do not include allocations from lakes because data on lake allocations were not immediately available.

Historical reported annual withdrawal data (1967-2004) for the A&T aquifer were acquired from the OWRB and analyzed. These data show that average annual withdrawal from the aquifer is 115,758 m^3/d, with a median withdrawal of 112,282 m^3/d. Within this period, minimum and maximum annual withdrawals were 48,783 m^3/d and 208,683 m^3/d respectively, in 1992 and 1977. Figure 2.5a shows a plot of the reported annual withdrawal for the 38-yr period. The Figure shows that the aquifer experienced more withdrawal in the mid to late 1970s. The 1980s was characterized by reduced withdrawal relative to the 70s. However, an upward trend appears to be emerging since 1993. The observed trends are consistent with precipitation patterns for the study area. Figure 2.5b is a pie-chart showing the distribution of the yearly withdrawal among the major water use classes from the aquifer. Irrigation is by far the dominant use class. The “other” category refers to withdrawal for agriculture, mining, industrial, commercial, and recreational purposes. Note that the withdrawals discussed here do not include amounts withdrawn for domestic, stock, and or small agricultural operations that use less than 17 m^3/d of water from the aquifer. Such uses do not require permitting from the OWRB and are generally not documented.

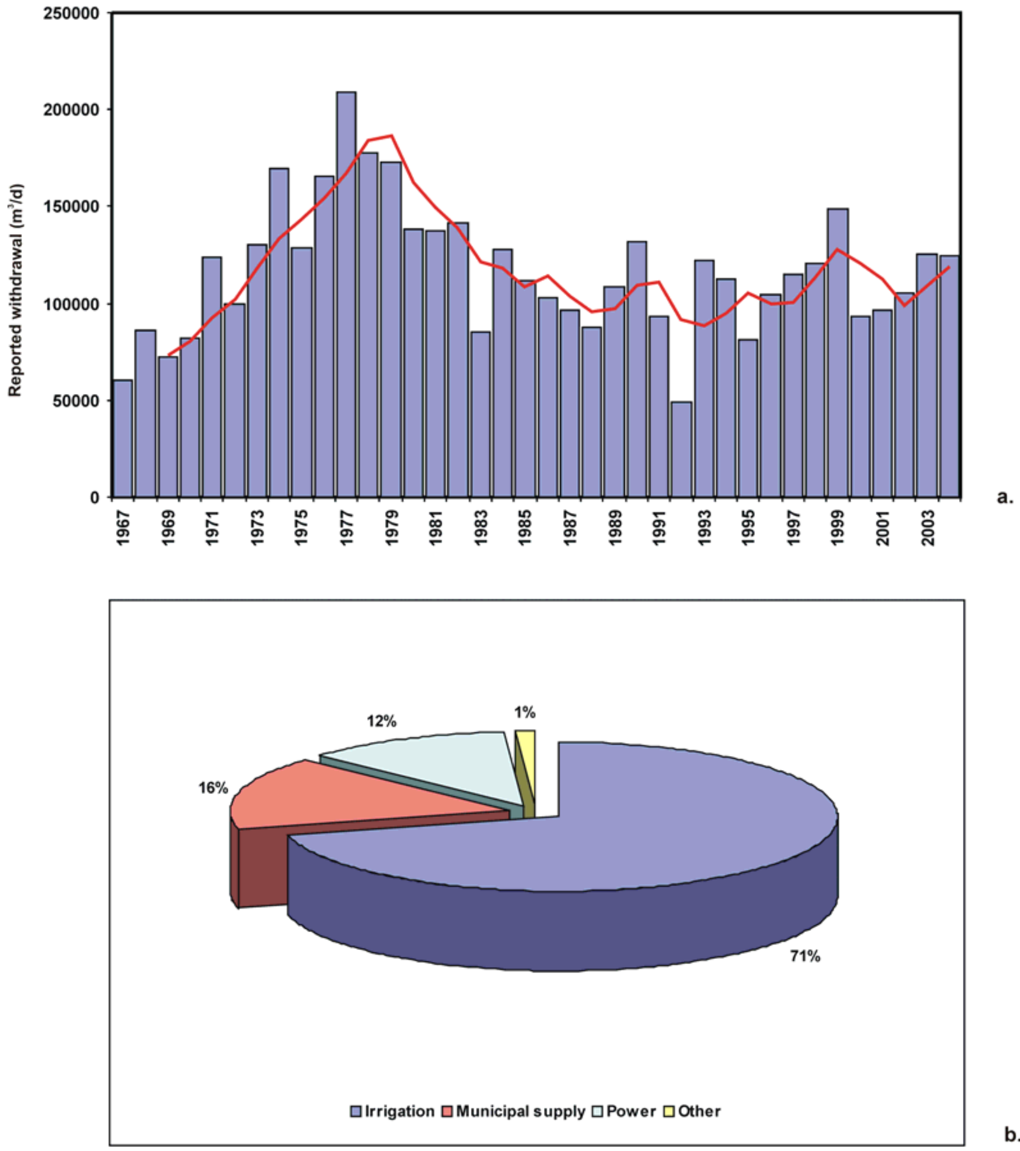

Figure 2.5: (a) Historical annual withdrawal from the A&T aquifer (1967-2004). Bold line is the 3-yr moving average, (b) distribution of the total annual withdrawal by use class.

2.6 Previous Related Studies within the BNCR basin

The first modeling study of the A&T aquifer was initiated by the U.S. Geological Survey (USGS), supported by the Oklahoma Water Resources Board (OWRB), and carried out by Davis and Christenson (1981). The goal of the study was to provide an in-depth understanding of the aquifer's hydrogeology, which is required for the proper development and management of the aquifer. In the study, the authors utilized data from approximately 900 wells to develop a 2-dimensional (2-D) groundwater model using the 'digital simulation model' program by Trescott et al (1976a). The 2-D model was used to predict the effects of prolonged groundwater pumping (1978 – 2020) on the alluvial aquifer based on the 1977 well distribution and pumping rates. Both the well density and pumpage rates were kept constant throughout the simulation period. Under this scenario, their results indicated that the average saturated thickness of the aquifer would decrease by only 0.5 m by the year 2020. However, the rate of decrease would vary unevenly across the aquifer. Well data used for the modeling exercise were from a prior study conducted between 1977-79 (Davis et al., 1980), which inventoried existing groundwater wells and test holes within the aquifer, as well as their uses. A total of 900 wells were documented and monthly water-level measurements were made for more than 30% of the wells. These data, together with previous site geologic and hydrologic information documented by Marine and Schoff (1962), Wood and Stacey (1965), and Morton (1980), were used by the authors to develop a conceptual model for the alluvial aquifer. Thus, from a modeling standpoint, most of what is known about the A&T aquifer today is from the Davis and Christenson study. There has been no update of the study, neither has there been another systematic study of the alluvial aquifer. However, within the BNCR drainage basin, pertinent studies, focusing primarily on climate and streamflow, have been carried out. For example, Zume and Tarhule (2006) analyzed the basin's precipitation and streamflow time series over the period 1894-2003, for trends and periodicities (included here in the next chapter). The study reported statistically significant trends for annual precipitation at several individual gauging stations but not for the region as a whole. Additionally, the study reported inter-annual to decade-scale modes of variability both in the precipitation and streamflow time series. The findings about trends were consistent with those reported in earlier studies by Wahl (2001), Wahl and Tortorelli (1996), and Wahl and Wahl (1988) even though the studies spanned different temporal and spatial scales. The work by Wahl and Tortorelli (1996) specifically examined precipitation, streamflow, baseflow, and annual peak discharges in the Beaver-north Canadian river and its tributaries for trends. Using the Mann-Kendall test for trend, moving averages, and comparisons of median and average flows for specified periods, the authors reported that the total annual volume of flow and the magnitudes of annual peak discharges measured at most gauging stations in the basin have declined significantly. An earlier study by Wahl and Wahl (1988) drew similar conclusions. Additionally, Wahl (2001) investigated the impacts of groundwater level declines on streamflow in the Oklahoma panhandle, including parts of the study area. He concluded that declining groundwater levels are responsible for the decreasing streamflow in the BNCR. These studies have provided valuable pieces of information that are incorporated into the present study.

Although no formal study of the A&T aquifer has occurred within the last twenty years, the OWRB has continued to document developments within the aquifer. For example, up-to-date well completion reports and logs are available on the OWRB website. Similarly, the OWRB monitors several wells within the aquifer through its mass measurement program and maintains a database on groundwater withdrawal from the aquifer.

2.7 Background to Groundwater Modeling

Groundwater modeling is a very important tool for performing complex hydrogeologic analyses, which leads to informed decision about groundwater development and management. It can be used to evaluate existing well systems for quantity and quality impacts as well as to assess the potential impacts external stresses (e.g. climate or pumping) might have on a hydrogeologic environment. The modeling approach attempts to replicate the physical processes that occur in a real aquifer by incorporating actual system complexities into a mathematical formulation. For example, flow in an aquifer depends on a number of geologic and hydrologic parameters, including the porosity of geologic units, the hydraulic conductivity, the storage capacity, as well as the physical boundaries (geologic and hydrologic) within the system. In order to accurately replicate the actual system therefore, a flow model must represent as realistically as possible these parameters, including their spatial distributions over the model domain. The ultimate goal of the modeling exercise is to predict the distribution of the hydraulic head, both in space and time, within the modeled system. Once produced, a groundwater model can be updated periodically as new understanding of the physical system becomes available.

The development of an accurate groundwater flow model, however, depends on a thorough conceptual understanding of the physical system and the application of appropriate boundary conditions over the problem domain. The mathematical formulation is complex, nevertheless, the underlying theories and assumptions have been well simplified in many standard texts (e.g. Freeze and Cherry, 1979; Fetter, 2001) and documentations accompanying computer codes (e.g. McDonald and Harbaugh, 1988). Thus, for brevity, details about the mathematical concepts are not replicated in this dissertation. The partial differential equation (pde) governing three-dimensional groundwater flow in porous media is simply presented without the rigorous derivations. A detailed derivation as well as the underlying assumptions can be found, for example, in Bear and Verruijt (1987).

Broadly speaking, groundwater flow through porous media is a three- dimensional (3-D) process, involving both horizontal and vertical flow fields, particularly around system boundaries such as surface water bodies and groundwater divides. However, two-dimensional (2-D) groundwater flow models (e.g.Trescott et al, 1976a; Bakker, 2003) have been used to address several groundwater problems. Realistically, 2-D models approximate a 3-D problem with the assumption that the vertical extent of the modeled aquifer is small compared to its horizontal dimension. Under such assumption, flow in the aquifer could be considered to be entirely horizontal, which means that the hydraulic head $h = h(x, y, t)$ in the aquifer is independent of the z direction, reducing a three-dimensional problem to a two-dimensional one. This is the so-called Dupuit approximation (Anderson and Woessner, 1992). While this approach is mathematically friendlier, the assumption of horizontal flow is rarely practical under actual field conditions (Bear and veruijt, 1987). In alluvial aquifers for example, vertical flow is induced in the vicinity of partially penetrating streams, wells, rivers, and springs, which violates the Dupuit approximation. As a result, 3-D groundwater flow models are increasingly used for more realistic simulation of hydrogeologic processes (e.g. Jagelke and Barthel, 2005; Dogan and Motz, 2005). Fortunately, recent advancements in the computational efficiency of personal computers have made the application of full 3-D models relatively easy. This study utilizes a full 3-D model to appropriately represent the partially-penetrating streams and wells on the study site.

2.7.1 The Groundwater Flow Equation

The 3-D movement of groundwater of constant density through saturated porous media may be described by the pde in equation (1) below (e.g. McDonald and Harbaugh, 1988).

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z}) + W = S_s\frac{\partial h}{\partial t} \qquad (1)$$

Where, K_{xx}, K_{yy}, and K_{zz} are components of the hydraulic conductivity in the *x, y*, and *z* directions (L/T);

h is the hydraulic head (L);

S_s is the specific storage of the porous medium (L^{-1});

W is a volumetric flux per unit volume (T^{-1}) and is a sink/source term, positive for inflow to the system and negative for outflow; and *t* is the time (T).

Generally, the hydraulic conductivity (*K*) and the specific storage (S_s) may be functions of space (i.e. $K = K(x,y,z)$ and $S_s = S_s(x,y,z)$ but *W* may be a function of both space and time (i.e. $W = W$(x,y,z,t).

Equation (1) derives from a combination of the mass conservation equation and Darcy's law. Two major assumptions make eqn (1) appropriate for modeling groundwater flow under non-equilibrium conditions in a heterogeneous and anisotropic medium. First, the components of the hydraulic conductivity tensor are assumed to be co-linear with the principal coordinates (*x, y, z*). In situations where the geology of an aquifer induces a violation of this assumption it may be necessary to modify the governing equation to utilize all components of hydraulic conductivity tensor (Anderson and Woessner, 1992). This was not the case in the present study. The second assumption is that the density of water must be constant; if not, a density-dependent governing equation must be used. This study also used the assumption of constant density of water.

It must be noted that the storage term, S_s in eqn (1) represents conditions in a confined aquifer. For unconfined flow, such as the case in this study, the S_s term must be replaced with S_y; the specific yield. The specific yield is a parameter that indicates the amount of water released from storage by gravity drainage when there is a lowering of the water table.

The solution to eqn (1) produces the three-dimensional distribution of the hydraulic head in the modeled aquifer (McDonald and Harbaugh, 1988). In principle, eqn (1) can be solved analytically to obtain an exact solution. Practically, however, an analytical solution is extremely difficult to achieve, thus, numerical solutions using either the finite-difference (FD) or the finite-element (FE) methods are more commonly used to obtain an approximate solution. Note that eqn (1) represents continuous flow in porous media. The numerical approach reduces the continuous equation into a set of discrete algebraic equations, which are solved using different techniques. Whether the FD or the FE method is used is more or less a matter of choice, however, generally, groundwater modeling codes using the FD approach (e.g. MODFLOW) are more common than those of the FE. Although the FE method provides a more systematic means of handling irregularly-shaped domains and boundary conditions, its theory is much more complex. For example, it offers several choices of basis functions and methods for estimating the element integrals, which only adds to its complexity. On the other hand, the theory of the FD method is much simpler to understand and code. Additionally, the FD scheme can better represent systems with variable hydraulic conductivity by using the harmonic mean at cell interfaces, which allows for continuous interfacial fluxes. Another advantage of the FD method is that it requires less computer memory. For this study, MODFLOW, a FD code, was used. A brief description of the FD approach is given below.

2.7.2 The Finite-Difference (FD) Approximation

Under the FD method, the continuous flow system, represented by eqn (1), is discretized into rectangular grid cells. Each grid cell has a point called a node, where the hydraulic head is calculated. At each node, eqn (1) is approximated with an algebraic expression involving values of the hydraulic head. The approximation of eqn (1) at every node within the problem domain leads to a system of algebraic difference equations, which can be solved numerically to obtain head values at each node. The discretization works under the assumption that all material properties are constant or linearly variable within a grid cell. Figure 2.6 shows a representative 3-dimensional finite-difference computational molecule. Points labeled A-G are representative of nodes on a grid. The general form of the finite-difference expression for the molecule is given in equation (2) (e.g. Anderson and Woessner, 1992).

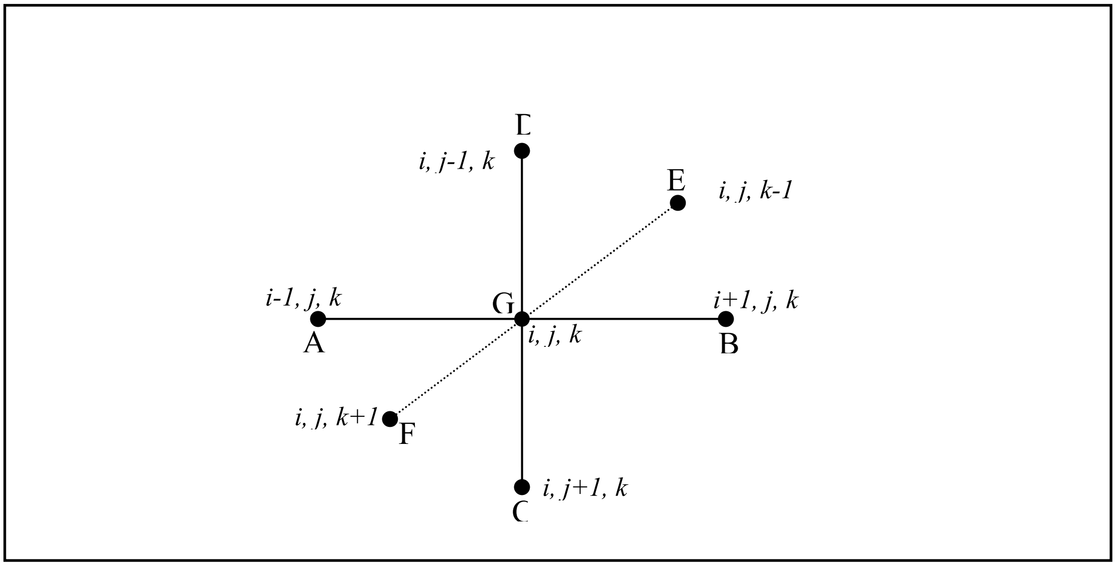

Figure 2.6: Three dimensional finite-difference molecule

$$Ah_{i-1,j,k} + Ch_{i,j,k+1} + Bh_{i+1,j,k} + Dh_{i,j-1,k} + Fh_{i,j,k+1} + Eh_{i,j,k-1} + Gh_{i,j,k} = RHS_{i,j,k} \quad (2)$$

where

$h_{i,j,k}$ is the hydraulic head at cell i,j,k.

Equation (2) shows that the computation of head at node i,j,k ($h_{i,j,k}$) involves the head at the node itself and those at the six surrounding nodes. The coefficients A-G are functions of the hydraulic conductivity between the nodes. The $RHS_{i,j,k}$ term includes the storage and the source/sink terms on right hand side of equation (1).

2.7.3 Boundary Conditions

In order to obtain a solution to the groundwater flow equation both initial conditions (heads at time t = 0) and boundary conditions must be specified within the flow domain. Boundary conditions may either be physical boundaries within the hydrogeologic system (e.g. a stream, a lake, a geologic feature, etc.) or an approximation of the domain beyond the physical boundaries (hydraulic boundary). It is much easier to represent a physical boundary in the model than it is for a hydraulic one (e.g. use of flow lines). Hydraulic boundaries, wherever necessary, must be handled with care.

Three types of boundary conditions are commonly used for groundwater flow systems; (i) specified head or Dirichlet; (ii) specified flow or Neumann boundary; and (iii) head-dependent or Cauchy boundary. The values of the hydraulic head in the flow domain must satisfy the assigned boundary conditions in order to obtain a valid solution. Table 2.2 shows the mathematical form for each boundary type. The choice of a particular boundary type depends on the objectives of the study and perhaps, how the problem is conceptualized. However, it is important to note that flow boundary conditions are not just mathematical constraints but also represent sources and sinks within the hydrogeologic system. Thus, they must be represented correctly for an accurate model solution.

Table 2.2: Commonly used boundary conditions

Boundary type	Designation	Formal name	Mathematical form
1	Specified head	Dirichlet	h(x,y,z,t) = constant
2	Specified flow	Neumann	dh(x,y,z,t)/dn = constant
3	Head-dependent flow	Cauchy	dh/dn + ch = constant (c is also a constant)

In MODFLOW, several boundary condition packages (BC) are provided for simulating the relationship between the modeled system and surrounding systems. Flow BC packages include Constant Head (Type 1), River (Type 3), Stream (Type 3), General Head (Type 3), Drain (Type 3), Well (Type 2), Recharge (Type 2), and Evapotranspiration (Type 3). An excellent discussion of the various types of hydrogeologic boundaries and their representation in groundwater flow models can be found in Reilly (2001).

2.8 Model Conceptualization

Typically, the development of a groundwater flow model involves a number of critical stages or protocols (e.g. Anderson and Woessner, 1992), including; (i) establishing the purpose for the model; (ii) developing a conceptual model; (iii) selecting an appropriate computer code for solving the groundwater flow equation; (iv) assembling and running the model; (v) calibrating the model and testing the sensitivity of model parameters to model performance. A calibrated and tested model can then be used for predictive purposes.

The modeling exercise in this study followed the above protocol. This section describes the conceptual model used to mathematically model the A&T aquifer. For a groundwater system, the conceptual model is a working description or representation of the physical processes that govern groundwater flow in the aquifer being modeled. Thus, model conceptualization is, perhaps, the most critical step in developing a groundwater model (e.g. Kresic, 1997). Conceptualization involves assembling data on important aquifer variables, including physical dimensions, hydrostratigraphic units, system boundaries, and hydrogeologic parameters. Important hydrogeologic parameters that must be determined during model conceptualization include the hydraulic conductivity (K), and aquifer storage properties such as the specific yield (S_y) in the case of an unconfined aquifer. Additionally, all sources and sinks within the system must be accounted for. Specific data for the model conceptualization are provided below.

2.8.1 Aquifer Data

The physical dimensions of the A&T aquifer (refer to Figure 2.1) were obtained from Davis and Christenson (1981). The vertical structure however, was derived from logs of wells completed in the aquifer, provided by the Oklahoma Water Resources Board (OWRB), also available online at www.owrb.ok.gov/wd/search/search.php. On the basis of the well logs and the subsurface geology described in section 2.3 the aquifer was divided into three vertical layers. Using the same well logs the configuration of the base of the aquifer was determined by contouring depth to the bedrock at 400 discrete well locations. Aquifer top elevations were derived from a digital elevation model (30 m resolution). The aquifer was modeled as a single-layer, unconfined unit.

Physical boundaries of the aquifer, including streams, lakes, springs, and geologic features, were identified both physically on the site and on topographic maps. Data on streams were obtained both from the U.S. Environmental Protection Agency (U.S. EPA) BASINS program (www.epa.gov/waterscience/basins) and the U.S. Geological Survey (USGS) nwis database (http://waterdata.usgs.gov/ok/nwis). Lake data were acquired from the U.S. Army Corps of Engineers (Oklahoma office), who operate the lakes. Discharge data for the Boiling Springs was acquired from the Boiling Springs park office. These data were used to simulate the features in the model using appropriate boundary condition types.

Hydrogeologic parameters for the aquifer, mainly, the hydraulic conductivity (K) and the specific yield (S_y), were obtained from the Davis and Christenson (1981) report and used as initial inputs into the groundwater model. Davis and Christenson (1981) reported hydraulic conductivity values for the aquifer ranging from 0 to 49 m/day with an average of 18 m/day. The spatial distribution of K over the aquifer is uncertain but for this study, the variability of well yields across the aquifer was used to guide the initial distribution of K over the model domain. As with K, the initial specific yield (S_y) used in the model was a value of 0.29, reported by Davis and Christenson (1981). The above parameter values were adjusted during model calibration to obtain the final values used for model predictions.

Recharge to the A&T aquifer is primarily from direct precipitation seepage. Most recharge occurs between November and February when evapotranspiration is at its minimum (OWRB, 1997). Davis and Christenson (1981) estimated recharge for the study area to be approximately 25.4 mm/year, based on measurements of winter baseflow and estimations from monthly water balance. The estimation of recharge from baseflow follows from the continuity equation, which states that the rate of outflow is equal to that of inflow. Therefore, base flow, during non-flood periods, provides a good estimate of aquifer recharge. However, recharge estimation from baseflow measurements suffers a serious limitation in a watershed having dams because controlled dam releases may complicate baseflow measurements. The Beaver-North Canadian River (BNCR) is dammed at two locations. It is possible that releases from these dams may interfere with baseflow estimates at downstream gauges. Thus, for this study, recharge input to the groundwater model was assumed to be 10% of annual precipitation. Hence, consistent with the range in annual precipitation, the recharge varied from 6.96×10^{-5} m/day in the western part of the aquifer to 1.39×10^{-4} m/d in the southern part. This approach is consistent with results of studies relating groundwater recharge to percentages of regional precipitation (e.g. Szilagyi et al., 2005).

Other sources of recharge to the aquifer include leakage from surface water sources, irrigation return flows, and seepage from adjacent groundwater basins such as the Ogallala. No initial quantitative measures were available for these sources of inflow, except for irrigation return flow, which was assumed to be to be 20 % of total irrigation withdrawal, consistent also with Davis and Christenson (1981). A discussion of surface water-groundwater interaction in the study basin is described in the next section.

Discharge from the aquifer occurs through anthropogenic groundwater withdrawal for various purposes, leakage to the BNCR, evapotranspiration (E_p), and leakage into adjacent formations. Groundwater pumping is by far the largest source of discharge from the aquifer. Please refer to section 2.5 for a detailed discussion of aquifer withdrawal. Discharge into the BNCR, which occurs as baseflow, is the second largest source of outflow from the aquifer. Additionally, the water table map (refer to

Figure2.4a) indicates the aquifer discharges into adjacent formations. E_p within the aquifer limits is localized to a few areas close to the river channel where the water table is less than 3m below land surface (Davis and Christenson, 1981). No reliable quantitative measures of E_p were available at the time of this research. However, Davis and Christenson (1981) indicated that the amount of water loss from the aquifer through E_p is less than 1%.

2.8.2 Surface Water/Groundwater Interaction

The interaction between groundwater and surface streams is an important component of alluvial basin hydrology. Figure 2.7 illustrates the nature of the interaction between alluvial aquifers and overlying streams. Under non-pumping conditions the exchange of water between an alluvial aquifer and an overlying stream is largely controlled by the hydraulic gradient between the aquifer and the stream. For example, aquifer discharge (baseflow) to the stream occurs when the water table in the aquifer is higher than the stream stage (Fig. 2.7a) whereas stream leakage into the aquifer takes place when the stream stage is higher than the water table in the aquifer. Aquifer pumping upsets this natural pattern of flux exchange. A pumping well near the stream channel intercepts baseflow that would otherwise end up in the stream, depriving the stream of an important source of flow (see Fig. 2.7b). Excessive pumping from the well can reverse the hydraulic gradient between the aquifer and the stream such that the stream discharges more into the aquifer (induced stream infiltration). The sum of reduced baseflow and induced stream infiltration leads gives the total streamflow depletion, which has severe implications also for riparian ecosystems.

For groundwater modeling purposes, knowledge of the streambed hydraulic conductivity can greatly improve the estimates of stream-aquifer fluxes. Unfortunately, this parameter is difficult to determine precisely and, in most cases, a good initial guess is made and refined during model calibration (McDonald and Harbaugh, 1988). This also was the case in this study. A streambed hydraulic conductivity of 0.3 m/day was assumed for the BNCR and its tributaries. This is approximately 1% of the average aquifer hydraulic conductivity e.g. Adams and Bergmann, 1996).

Initial insight about stream/aquifer relations along the main course of the BNCR was gained by analyzing historical streamflow data at four USGS gauging stations within the study area. For example, analyses of the historical streamflow data (1947 -2003) at the Beaver, Woodward, Seiling, and Canton (1947-1993) gauging stations indicate that the segments from Beaver to Woodward, and from Woodward to Seiling, are influent. The segment between Seiling and Canton was considered a losing one. Whether a segment is gaining or losing was inferred from downstream changes in flow at successive sites (e.g. Barlow and Dickerman, 2001). A segment was considered to be gaining/losing if streamflow increased/decreased between two measurement stations. Losing conditions may result from natural stream-channel losses or from groundwater pumping. However, no specific studies about channel transmission losses were available on the river system. In determining gains and losses of streamflow, inflows from a tributary stream between a pair of gauging sites were subtracted from the total gains or losses between the sites. Note that these analyses were preliminary and the results were mainly to gain initial understanding of stream-aquifer dynamics. A complete picture of stream-aquifer interactions within the basin, derived from numerical simulation, is given in chapter 4.

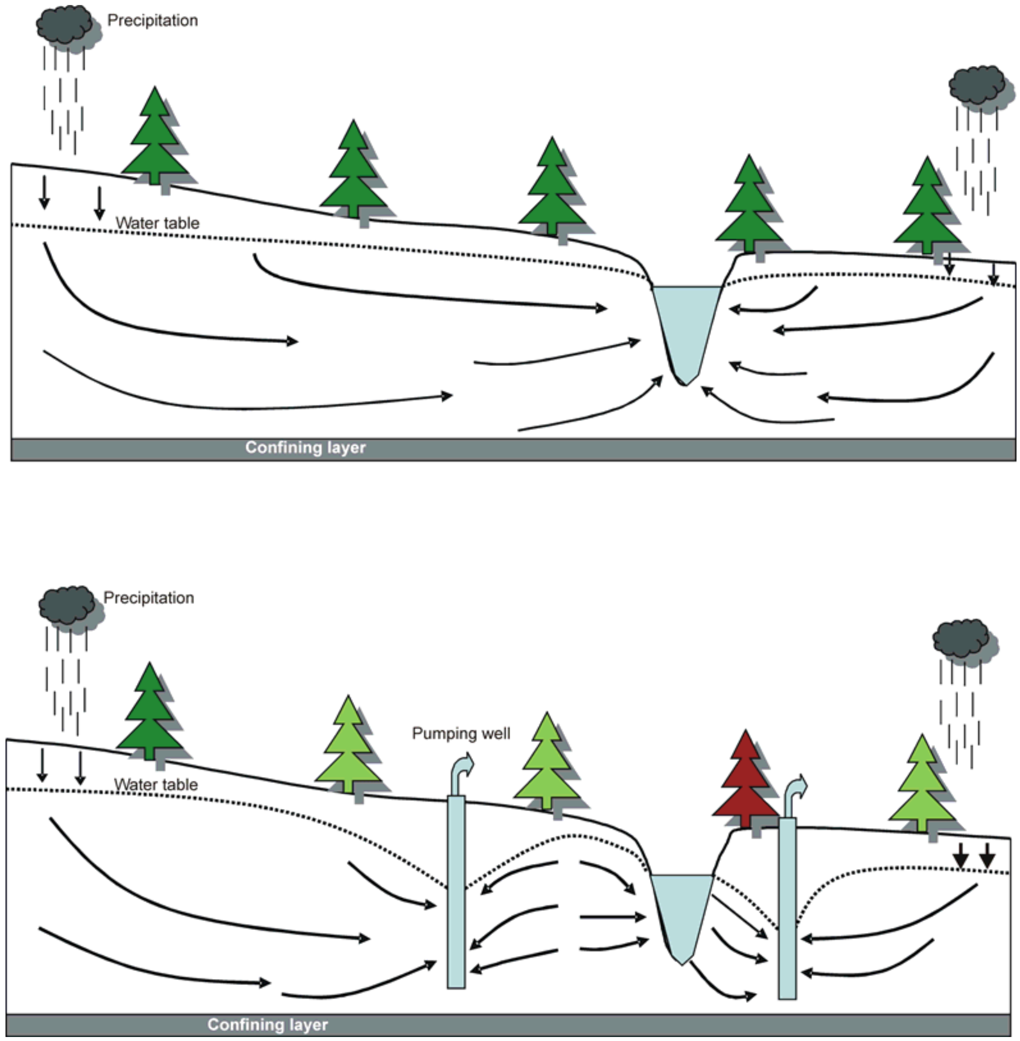

Figure 2.7: Groundwater-surface water interactions under (a) non-pumping condtions, (b) pumping conditions

2.9 Computer Code

Selecting an appropriate computer code that contains an algorithm to solve the governing groundwater flow equation is important in obtaining accurate model solution. It is important to choose a code that has been tested and verified. Verification of the code ensures that the computer program accurately solves the equations that make up the mathematical model. For this dissertation, the modular three-dimensional finite-difference groundwater flow model, MODFLOW (McDonald and Harbaugh, 1988) was used. MODFLOW was originally developed by the U.S. Geological Survey and has become a leading groundwater flow and transport code worldwide. The code now has several commercial pre- and post-processors, including Visual MODFLOW, PMWIN, Groundwater Vistas, GMS, among others.

2.9.1 Description of Modflow

MODFLOW is a modular three-dimensional finite-difference computer program that simulates groundwater flow through porous media. It simulates steady and non-steady flows in an aquifer under confined, unconfined, or a combination of both conditions (McDonald and Harbaugh, 1988). Additionally, it simulates flow from external stresses, such as flow to wells, area recharge, evapotranspiration, flow to drains, and flow through river beds.

MODFLOW was developed by the United States Geological Survey (USGS) and was originally documented by McDonald and Harbaugh (1984). Since its first version in 1984, the program has undergone several modifications as documented in McDonald and Harbaugh (1988; MODFLOW-88), Harbaugh and McDonald (1996a, 1996b; MODFLOW-96), Harbaugh et al (2000; MODFLOW-2000), and Harbaugh (2005; MODFLOW-2005). Each of these updates presents new capabilities or flexibilities that were lacking in previous versions. Additional to the major updates of the program, the modular structure of MODFLOW has allowed the addition of several packages. For example, packages that allow a more elaborate representation of stream-aquifer relations in the model have been added (Prudic, 1989; Prudic et al., 2004). Similarly, new solver packages such as the Preconditioned Conjugate Gradient (PCG; Hill, 1990), and the Geometric Multigrid (GMG) solver (Wilson and Naf, 2004) packages have been added. Although MODFLOW was originally conceived to be solely a groundwater flow model, its scope has been broadened over the years to give it capabilities for solving related processes such as the transport equation (Konikow et al., 1996)and the parameter estimation equations (Hill et al., 2000).

What distinguishes MODFLOW from previous finite-difference groundwater flow codes such as those by Trescott (1975) and Trescott and Larson (1976b), is its modular structure. This means that the program consists of a main code with a series of independent packages. Each package allows an independent examination of a specific feature in the hydrogeologic system. For example, the STR package allows the independent simulation of stream-aquifer interactions. Packages in MODFLOW include, the Recharge (RCH), Well (WEL), Drain (DRN), River (RIV), Stream (STR), Evapotranspiration (EVT), General Head Boundary (GHB), Block Centered Flow (BCF), Output Control (OC), Basic (BAS), and several solver packages. The modular structure of MODFLOW allows the addition of new packages without the need to modify existing packages. Because of this structure, MODFLOW has become the most widely used groundwater model worldwide.

For this study, Visual MODFLOW (VM), a proprietary product of Waterloo Hydrogeologic Inc (2005), was used. The version 4.1 of VM used for this study is window-based and has a fully integrated graphic-user-interface (GUI) that enhances pre- and post- processing of input and output data for MODFLOW.

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Chapter 3

Precipitation and Streamflow Variability in Northwestern Oklahoma, 1894-2003

PRECIPITATION AND STREAMFLOW VARIABILITY IN NORTHWESTERN OKLAHOMA, 1894-2003

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Abstract

This paper utilizes time-series analysis to examine precipitation and streamflow variability in northwestern Oklahoma over the period 1894-2003. Trends and periodicities in the hydroclimatic variables were investigated using, respectively, Mann-Kendall test and continuous wavelet transform (CWT) methods. Statistically significant trends were found in annual precipitation at individual gauging stations but with no spatial coherence to suggest evidence of large-scale climatic forcing. No significant trends were found for the regionalized average annual or seasonal precipitation. Annual streamflow exhibited declining trends upstream of Woodward. The CWT analysis revealed interannual to decadal modes of variability in precipitation. Similar but less sustained cycles are also found in streamflow. Correlation of precipitation with the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) indices suggests precipitation for northwestern Oklahoma is associated with Pacific sea surface temperatures (SST).

Key words: Precipitation variability, ENSO, PDO, streamflow, northwestern Oklahoma

3.1 Introduction

Embedded within the hydroclimatic time series for a location are various scales and patterns of variability, the analysis of which may provide useful insights for water resources planning, and about the nature of the causative processes. Such analysis is especially important where anthropogenic impacts superimpose upon, and complicate, the natural patterns of variability.

Time-series analysis is a powerful means for identifying embedded patterns of variability in a hydroclimatic signal because it disintegrates the signal into different components such as trends, jumps, and periodicities, each of which contributes uniquely to the overall time-series structure.

Many studies employing time-series methods have been carried out for the United States southern Great Plains, a drought-prone but agriculturally important region. For example, Garbrecht et al (2004) examined trends in annual precipitation, streamflow, and evapotranspiration for 10 watersheds across Nebraska, Kansas, and Oklahoma. They detected significant increasing trends in all three parameters for all the watersheds. Wahl and Tortorelli (1996) investigated possible changes in streamflow in western Oklahoma resulting from anthropogenic impacts and precipitation change. They reported significant decreasing trends in discharge at 25% of the gauging sites. Declining streamflow was attributed to anthropogenic impacts, particularly, groundwater withdrawal. The study did not consider precipitation at individual gauging sites but monthly and annual averages for the entire Panhandle climate division. No regional trend was detected in annual precipitation but a significant increasing trend was reported for March and a decreasing

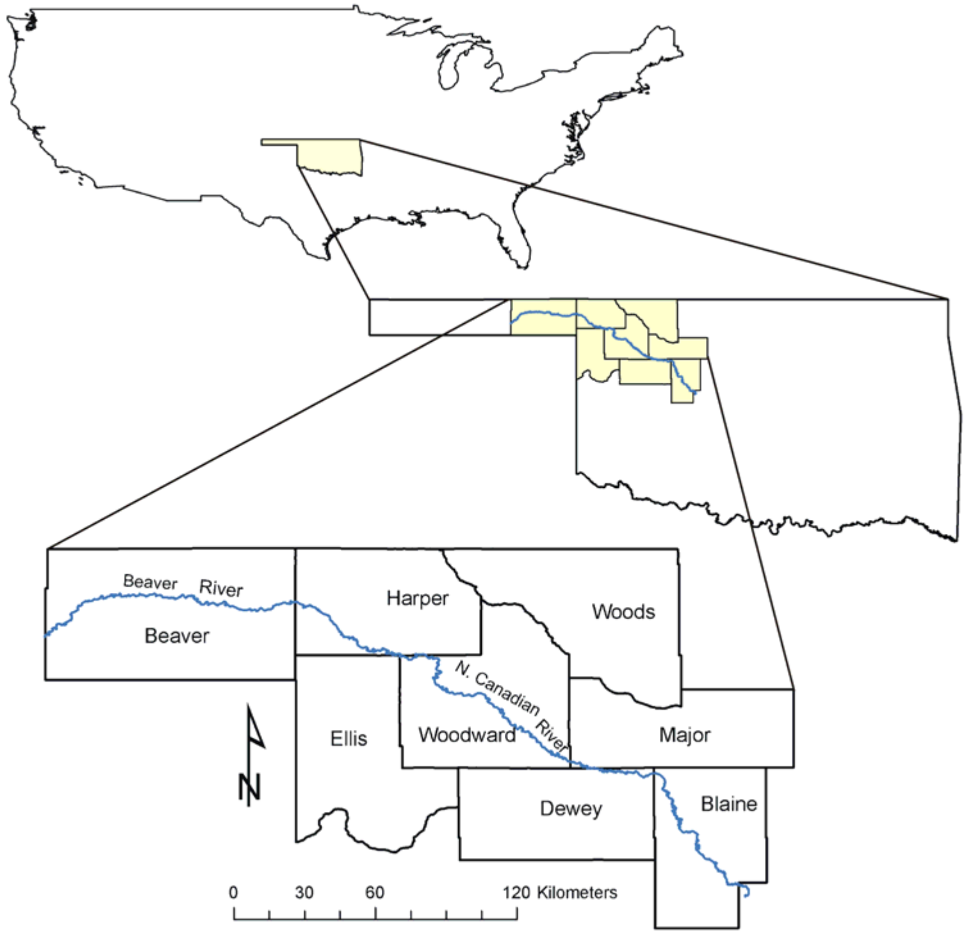

Figure 1: Study area in northwestern Oklahoma

one for July. An earlier study by Wahl and Wahl (1988) reported similar results for streamflow and annual precipitation in the same region. Another study by Hu et al. (1998) examined annual precipitation data covering parts of Missouri, Kansas, and Nebraska using wavelet analysis. The study found decade-scale oscillations in the regional annual precipitation. Elsewhere, studies such as those by Lettenmaier et al. (1994), Lins and Slack (1999), Groisman et al. (2001), and Xu et al. (2004), have used the time-series method to analyze different hydroclimatic series for trends.

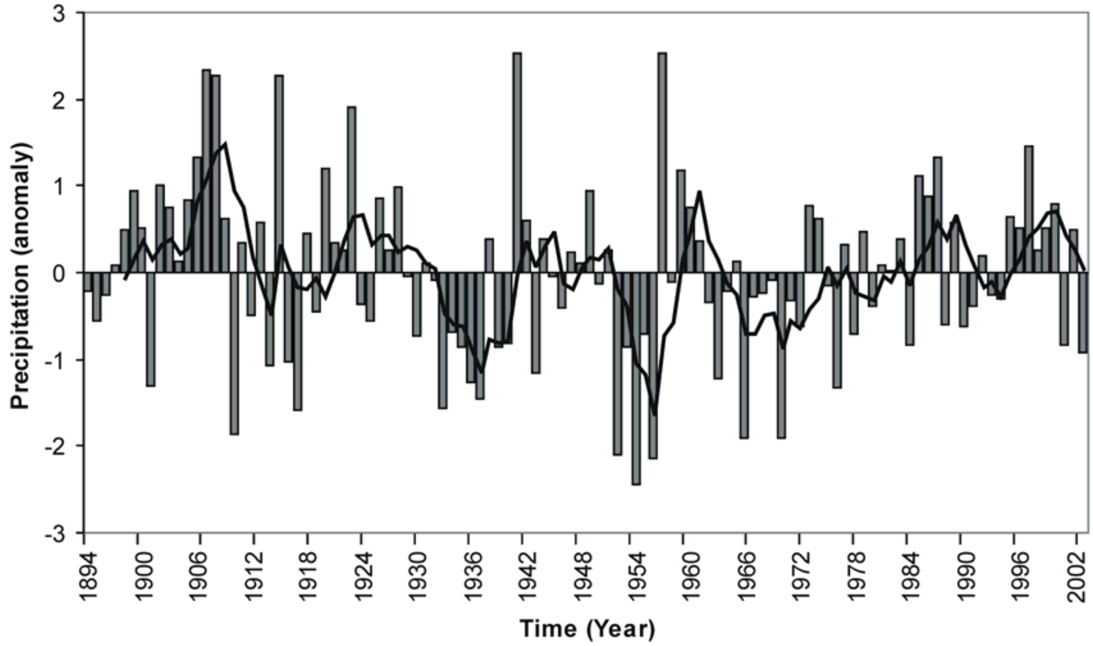

Figure 2: Standardized precipitation (anomaly) plot for northwestern Oklahoma (1894-2003). Thick line is the 5-year running mean.

In this study, we investigate the occurrence of trends and periodicities in precipitation and streamflow time series at three time scales: monthly, seasonal, and annual, using Mann-Kendall trend test and continuous wavelet transform (CWT) methods. Additionally, the precipitation series are correlated with Pacific sea surface temperature (SST) indices associated with the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Several studies, such as those by Trenberth and Branstator (1992), Trenberth and Guillemont (1996), Ting and Wang (1997), Barlow et al., (2001), Schubert et al. (2004), and Seager et al. (2005), have linked various aspects of the Great Plains precipitation to variations in Pacific SST.

3.2 Study Area, Data and Methodology

3.2.1 *Study Area*

The study area in northwestern Oklahoma extends from latitudes 36^0 - 37^0 N and longitudes 98^0 - 100^0 W. It covers a total area of 2150 km^2 and comprises the drainage basin of the Beaver-North Canadian River (Fig. 1).

Although agriculture is the most important economic activity in northwestern Oklahoma, the region is drought-prone and suffers periodic water shortages. The standardized precipitation anomaly plot (Fig. 2) shows recurrent droughts in 1930s, 1950s, and 1960s. Regional drought conditions are exacerbated by high annual evaporative losses (1422 to 1625 mm) in excess of annual precipitation (OWRB, 1997). This, together with prevailing surface-water quality issues, poses a serious threat to water resources availability in the area.

3.2.2 *Data*

Long-term monthly precipitation records (1894 - 2003) for twenty seven (27) gauging stations across the study area were obtained from the Oklahoma Climatologic Survey (OCS). These data are part of the National Weather Service cooperative stations network, and can also be accessed on-line at http://climate.ocs.ou.edu/coop.php/. Streamflow discharge data for five gauging stations (1937-2003) in the Beaver-North Canadian River system were retrieved from the U. S. Geological Survey (USGS) database (http://waterdata.usgs.gov/ok/nwis). Figure 3 shows the distribution of precipitation and streamflow gauging stations over the study area. The Niño 3.4 index (bounded by 5^0N-5^0S, 150^0-90^0W) was obtained from the National Weather Service-

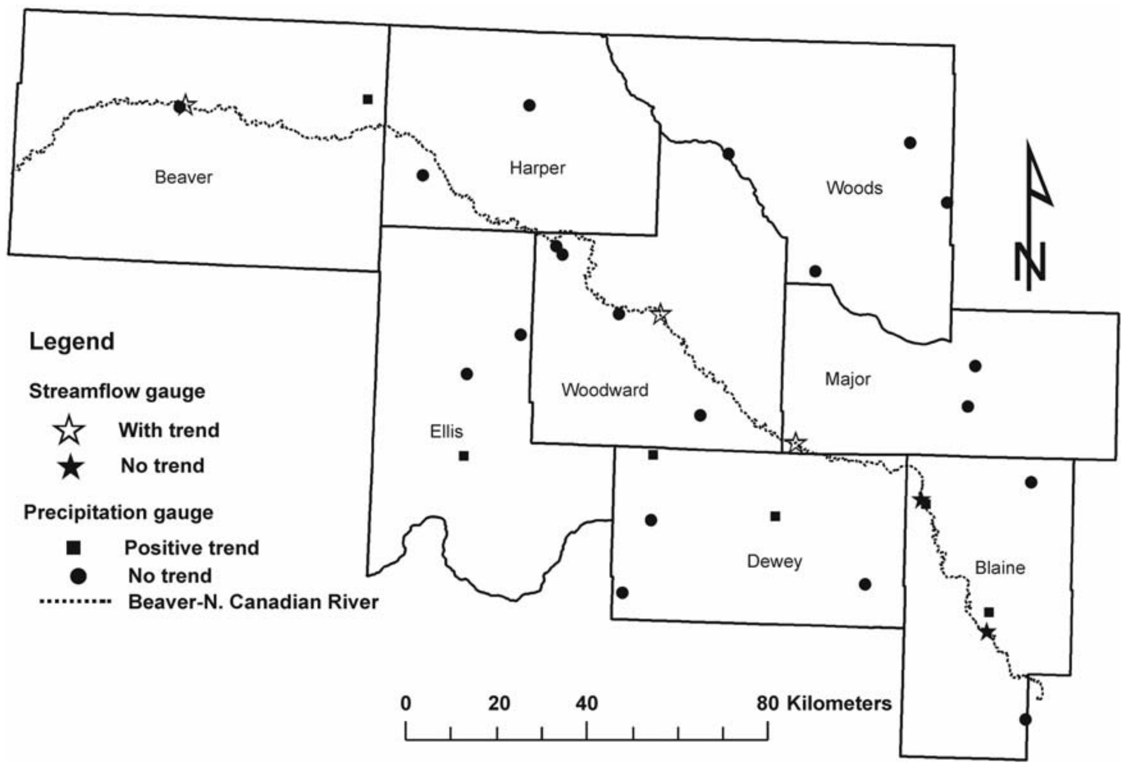

Figure 3: Study area showing location of data stations and trend patterns for annual precipitation and streamflow. Significant trends are at the 95% confidence level.

Climate Prediction Center website at www.cgd.ucar.edu/cas/catalog/climind/niño_3_3.4/ indices. Data for the PDO were downloaded from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) data archives (http://jisao.washington.edu/pdo/ pdo.latest). The PDO is defined as the leading principal component of monthly SST anomalies in the North Pacific Ocean poleward of 20^0N (Mantua et al., 1997; Zhang et al., 1997).

3.2.3 *Methodology*

Trend analysis. The non-parametric Mann-Kendall (MK) test (Kendall 1938) was used to examine both the precipitation and the streamflow records for trends. Trend tests were performed on all 27 precipitation and 5 streamflow series, each of which had at least 40 years of record during the study period. The precipitation data were aggregated into monthly, seasonal, and annual time series while those for streamflow were grouped into seasonal and annual time periods.

The MK is a test of randomness against monotonic trend. It is very popular for analyzing hydroclimatic time series (e.g. Douglas et al., 2000; McCabe and Wolock 2002; Yue and Wang 2002; Piccarreta et al., 2004) for a number of reasons: first, it is a rank-based method and therefore less sensitive to outliers in the data series compared with parametric methods; second, it makes no assumptions about the nature of the probability distribution underlying the data; third and finally, the test works well for both censored and data with missing values (Molnár and Ramírez 2001). However, the MK test performs poorly on serially correlated and seasonal data. Consequently, its application to such data requires appropriate adjustments (e.g. Douglas et al., 2000). In this study, we applied the MK test to independent and non-seasonal data such as annual precipitation and streamflow, as well as monthly data across years (e.g., Molnár and Ramírez 2001).

The MK test statistic (S-statistic) is calculated as (e.g., Douglas et al., 2000);

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_i - x_j) \qquad (1)$$

where x_i and x_j are the ordered data points at times *i* and *j,* in the time series, and *sign* () is defined as

$$sign() = \begin{cases} +1, x_i > x_j \\ 0, x_i = x_j \\ -1, x_i < x_j \end{cases} \qquad (2)$$

Under the null hypothesis (H_0) that x_1, x_2, ----, x_n are independent and identically distributed random variables, S is asymptotically normally distributed with mean of zero and variance given by equation 3 (Kendall, 1938).

$$\mathrm{var}(s) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{g} t_i(t_i - 1)(2t_i + 5)}{18} \qquad (3)$$

where *n* is the sample size; g is a correction term representing the number of groups with tied values; t_i is the number of ties in group *i*, and the summation is over all ties. The standardized normal test statistic, *z*, is calculated as in Eq. 4 using the values of S and var(S) in Eqs. (1) and (3) respectively.

$$z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{var}(S)}} & for\ S > 0 \\ 0 & for\ S = 0 \\ \frac{S+1}{\sqrt{\mathrm{var}(S)}} & for\ S < 0 \end{cases} \qquad (4)$$

The presence of a statistically significant trend is evaluated using the *z* value. A positive *z* value indicates an upward trend, while a negative one indicates a downward trend.

To perform the trend test, we used the Makesens program, provided by the Finnish Meteorological Institute (www.fmi.fi/organization/contacts_25.html. The program estimates also the magnitude,β, of the trends using the non-parametric SEN's slope estimator. The slope is estimated as:

$$\beta = median(\frac{x_i - x_j}{i - j}) \text{ for all } j < i. \qquad (5)$$

where $1 < j < i < n$. Makesens incorporates two-tailed significance test in which both trend and the slope significance could be tested at various significance levels.

Continuous wavelet analysis (CWT). Continuous wavelet transform (CWT) is a mathematical tool that decomposes a 1-dimensional time-series into a 2-dimensional frequency-time space (e.g., Mallat, 1989; Jurry and Melice, 2000). This is accomplished by the use of analyzing basis functions called "daughter" wavelets, which are derived from a "mother" wavelet by dilation and translation. The transformation facilitates the isolation of dominant modes of variability within the time series and their evolution in time (Torrence and Compo, 1998). A major advantage of CWT over other time-series analysis methods, such as the Fourier transform, is that the basis functions used are localized both in time and frequency, which simultaneously preserves the temporal and spectral signatures of a series without assuming stationarity (Jiang et al., 1997; Ballester et al., 2004). This makes the wavelet transform a choice tool for hydroclimatic analyses because rarely are climatic and hydrologic time series stationary nature.

In mathematical terms, given a mother wavelet Ψ, daughter wavelets ($\psi_{b,a}(t)$) can be derived by stretching and translating the mother wavelet. The analyzing function (daughter wavelet) is given as (e.g., Lau and Weng, 1995)

$$\psi_{b,a}(t) = \frac{1}{\sqrt{a}} \Psi(\frac{t - b}{a}) \qquad (6)$$

where a is the scale (dilation) parameter, and b is the translation of the scaled wavelet along the time axis. The factor $\sqrt{a}$ in (6) is an energy normalization factor that keeps the daughter wavelets' energy the same with the mother wavelet. To obtain the continuous wavelet transform (CWT) of a signal f(t), the analyzing wavelet ψ(t) is convolved with the signal. The result is the convolution integral (e.g., Lau and Weng, 1995),

$$C(b,a)=\frac{1}{\sqrt{a}}\int \psi^{*}(\frac{t-b}{a})f(t)dt \qquad (7)$$

where C (b,a) are the wavelet coefficients, which measure the degree of similarity between the daughter wavelet and the original signal in each section. ψ^{*} is the complex conjugate of ψ. The variation in the wavelet coefficients depicts the shifting level of similarity between the daughter wavelets and the original signal in time and frequency. Accuracy of results depend on the choice of a suitable mother wavelet. In this paper, we use the Morlet wavelet, which is one of the most widely used continuous wavelets in analyzing hydroclimatic time series (e.g., Lau and Weng, 1995; Hu et al., 1998; Torrence and Compo, 1998; Labat et al., 2001; Anctil and Coulibaly, 2004) to analyze precipitation and streamflow series. The Morlet wavelet consists of a plane wave modulated by a Gaussian envelope and is given by the expression (Torrence and Compo, 1998):

$$\varphi_0(\eta)=\pi^{-1/4}e^{(j\omega_0\eta)}e^{(-\eta^2/2)} \qquad (8)$$

Where φ_o is a wavelet function that depends on a non-dimensional time parameter, η; ω_o is the non-dimensional frequency, and $j = \sqrt{-1}$. The complex nature of the Morlet wavelet makes it suitable for detecting oscillatory pattern in a hydroclimatic signal. The program used for the CWT analysis is supplied by Terrence and Compo (accessed online at http://

paos.colorado.edu/research/wavelets/). In carrying out the analyses, the length of each time series was extended by padding its end with zeroes to the next power of two. This was necessary to reduce possible wrap-around effects near the signal end points, and to speed up the computation of the Fast Fourier Transforms (FFT).

3.3 Results and Discussion

3.3.1 *Trend Analysis*

Precipitation trends. Analysis of annual, seasonal, and monthly precipitation trend for northwestern Oklahoma suggest that precipitation amounts vary unevenly across the study area. Figure 3 shows the results for average annual precipitation at individual precipitation gauging stations. Six of the 27 stations (22%) show statistically significant ($P \leq 0.05$) positive trends. Five of these are located in the southern part of the study area, indicating wetter conditions there although not all stations in the south exhibit these trends. Only one station in the northwestern part of the study area indicates a positive trend, suggesting that the observed trends reflect local or site-specific conditions rather than a regionally-driven climatic influence. Indeed, when the average annual precipitation is regionalized, the Kendall's null hypothesis, H_o of a monotonic trend is rejected at the 95% confidence interval, indicating that regional precipitation has not changed significantly over the study period. This result is consistent with that of Wahl and Tortorelli (1996), who also reported no change in long-term (1895-1994) annual precipitation for western Oklahoma.

Figure 4a shows results of the trend analysis for regionalized seasonal precipitation. No statistically significant trend is observed for any of the seasons.

Monthly precipitation data analyzed at the 27 gauging stations show sixteen stations with at least one month of the year having a statistically significant ($P \leq 0.05$) trend. Four of these trends are negative while the remaining twelve are positive. However, the months in which these trends occur are not consistent from station to station. For example, positive trends occur in January and March at Vici (36.1500^0 N, 99.2833^0 W) but only in November and December at Canton (36.0500^0 N, 98.5833^0 W), and in August at Supply 1E (36.5667^0 N, 99.5500^0 W). April has the most number of trends (4) but there is no spatial clustering in the stations where these trends occur. The lack of agreement, both in the spatial and temporal location of these trends may suggest that they are random occurrences driven by site-specific conditions and not likely the result of large-scale regional climatic forcing. The result of regionalizing the monthly precipitation shows that only April has a statistically significant ($P \leq 0.05$) negative trend (Fig. 4b), indicating diminishing precipitation regionally for this month. This is in contrast to Wahl and Tortorelli (1996), who reported an increasing trend for March and a decreasing one for July in western Oklahoma. The discrepancy in results may possibly be due the different time scales used or a result of more recent prevailing climatic conditions in the study area.

Streamflow trends. Table 1 summarizes results of trend analysis for annual, seasonal, and monthly streamflow series in the Beaver-North Canadian River basin. Figure 5a shows the locations of the gauging sites as well as average flow conditions at each site.

Table 1. Summary of Trends Detected for Streamflow Time Series

Station	Annual	Seasons	Months
Beaver	(-)	all (-)	all (-) except Nov. (none)
Woodward	(-)	summer (-)	Jul. (-), Nov. (+)
Seiling	(none)	winter (+)	Jan., Nov., Dec. (+)
Canton	(none)	(none)	(none)
Watonga	(none)	(none)	(none)

(+) = positive trend, (-) = negative trend, (none) = no significant trend. Significance is at the 95% confidence level.

On the annual time scale, statistically significant ($P \leq 0.05$) negative trends are observed at the Beaver and Woodward stations. No significant trends are present in the downstream stations at Seiling, Canton, and Watonga. Similar results were reported by Wahl and Tortorelli (1996) for the same stations.

The seasonal-scale analyses (summer, spring, winter, and autumn) show statistically significant ($P \leq 0.05$) negative trends for all seasons for the Beaver River gauge at Beaver. Downstream, on the North Canadian River, there is a significant negative trend at Woodward for the summer season. In contrast, the station at Seiling shows a statistically significant positive trend in the winter. Farther downstream at the Canton and Watonga stations there are no seasons with either positive or negative significant trends in stream discharge.

Results for monthly analysis show spatial patterns similar to the annual and seasonal patterns above. The temporal locations however, appear to be random. For instance, on the Beaver River at Beaver gauging station, all months, except November show statistically significant ($P \leq 0.05$) negative trends. But the results in the North Canadian River are mixed. At the Woodward station for example, there is a significant ($P \leq 0.05$) negative trend for the month of July but a positive trend in November. Similarly, the station at Seiling exhibits positive trends in January, November, and December but no negative trends in any month. Again, there are no significant changes in monthly flow at the Canton and Watonga stations.

Thus, the preceding analysis suggests flow in the Beaver-North Canadian River has declined upstream of Woodward. The severity of the decline increases as one goes farther west. Recall however that the affected area showed no significant negative trend in precipitation. Consequently, decreasing streamflow is attributed to extensive groundwater withdrawal for irrigation in the drier western counties (e.g. Wahl and Wahl, 1988; Wahl and Tortorelli, 1996). One impact of this anthropogenic effect is that the upper reach of the Beaver River, which originally was a gaining stream (effluent), has become a losing (influent) one. In the eastern/southern parts of the study area however, irrigation pumpage is less due possibly to relatively more humid conditions. Groundwater data from the Oklahoma water resources board (http://www.owrb.state.ok.us/wd/search/search.php) indicates fewer irrigation wells in this area than the western part. The impacts of reduced groundwater utilization and wetter conditions in this region may explain the lack of negative trends in the North Canadian River reaches downstream from Woodward. Figure 5b shows illustrative groundwater hydrographs at four observation well locations (boxed numbers on Fig. 5a) across the study area. Notice the sharp decrease in groundwater levels at location 1 (west) contrary to the increasing levels at location 4 (east). The observed pattern supports earlier observations that groundwater utilization has impacted streamflow in the study area.

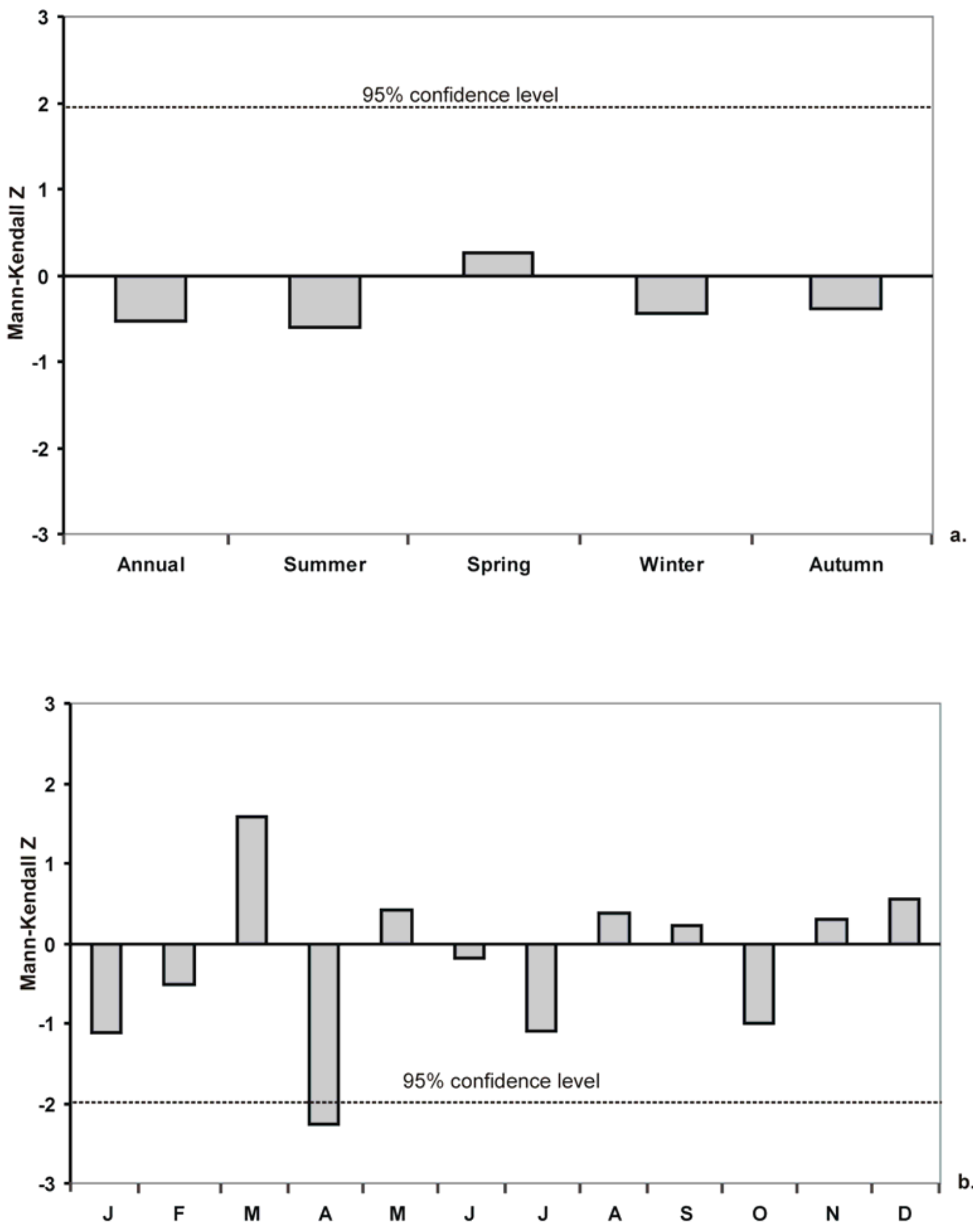

Figure 4: Results of trend analysis for regionalized (a) Annual and seasonal, (b) monthly precipitation.

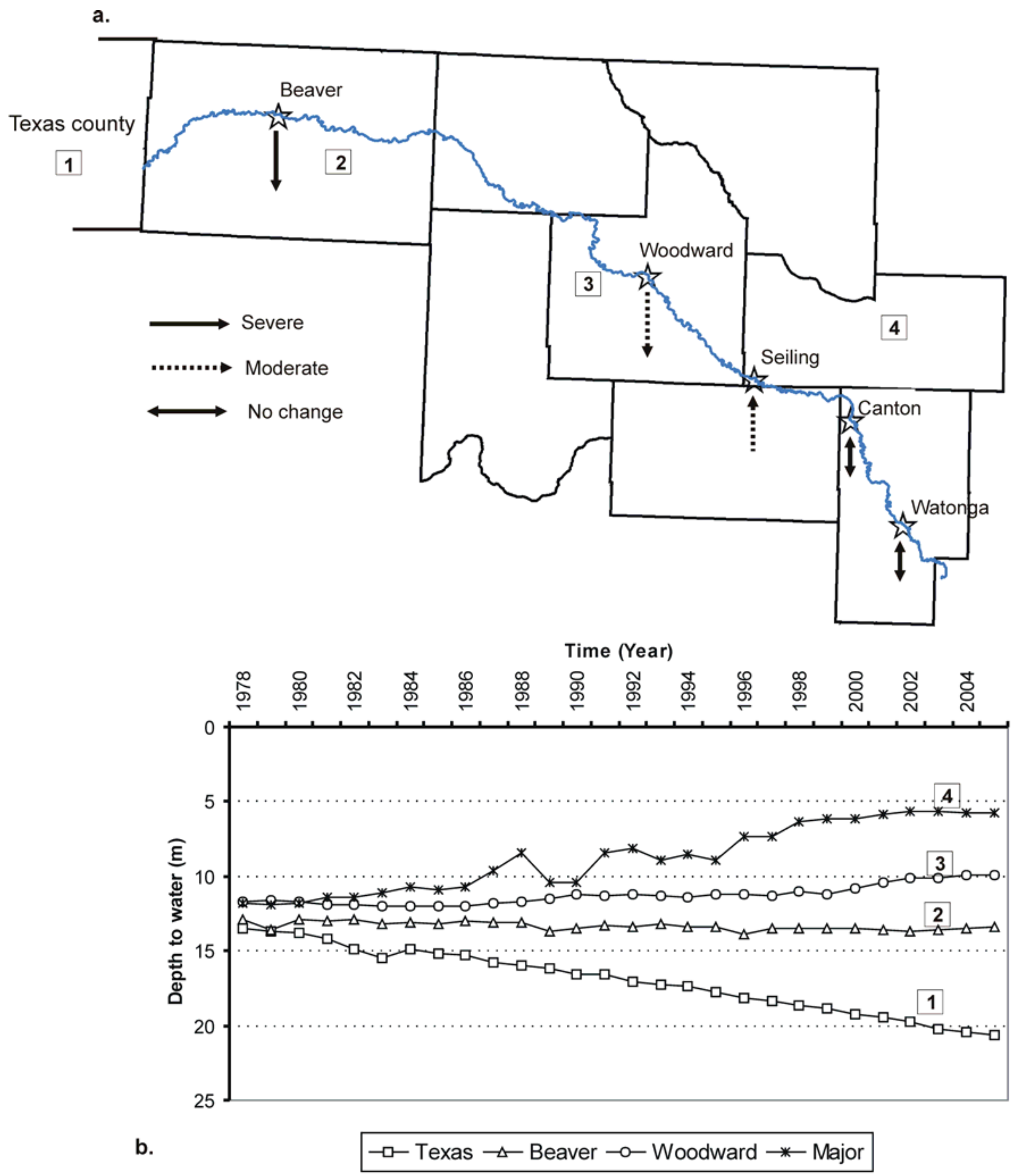

Figure 5: (a) Average flow conditions at streamflow gauging sites. Direction of arrow indicates trend direction (b) Groundwater hydrographs. Boxed numbers show corresponding location of wells in counties.

3.3.2 *Continuous Wavelet Transform (CWT)*

Precipitation. Figure 6b is the normalized CWT power spectrum for the regionalized average annual precipitation time-series shown in Figure 6a. The solid contour on the power spectrum encloses peaks above 95% confidence against a red-noise process (see Torrence and Compo, 1998). Only regions with wavelet power within this 95% confidence level are interpreted. The region below the solid curve defines the cone of influence, which is the region where edge effects, caused by zero-padding of the original time-series, have become significant. Hence, peaks in wavelet power within this region are presumed to be reduced in magnitude by the zero-padding (Torrence and Compo, 1998). The CWT spectrum shows that annual precipitation in northwestern Oklahoma fluctuates on interannual and decadal time scales. Bands of 2-4, 5-8, and approximately 10-12 year time scales are prominent on the spectrum. However, the decadal variations are weaker. The higher frequency components (2-4 yr) have significant peaks between 1900 and 2000, whereas lower frequency (beyond 5 yr) oscillations, which appear to mimic the drier portions of the original series (Fig. 6b), show peaks between 1905 and 1920, and in the 1950s. Less organized wavelet activity is observed beyond 1960 for the low frequency oscillations. The temporal distribution of peaks in the power spectrum is shown by the scale-averaged wavelet power spectrum in Figure 6c. The scale-averaged spectrum is the weighted sum of the wavelet power over a given range of scales, in this case, 2-10 years and is important for examining the temporal variability in power over the given band.

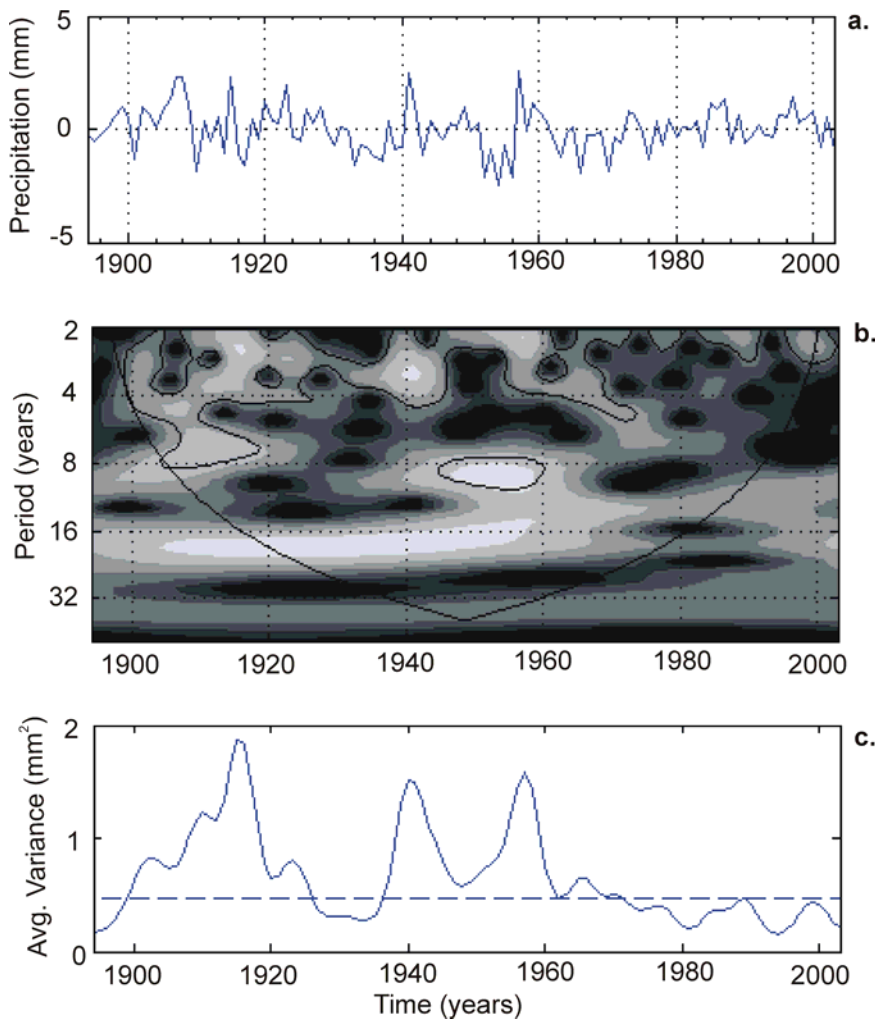

Figure 6: (a) Time series of regionalized average annual precipitation. (b) Its CWT power spectrum using the Morlet wavelet, (c) The 2-10 yr scale-averaged power spectrum.

Normalized CWT power spectrums (not shown) for seasonal precipitation (summer, winter, spring, and autumn) are produced in a similar manner as that in Figure 6. The associated time series of scale-averaged wavelet power for each season is presented in Figure 7. The power spectrum for summer precipitation shows a

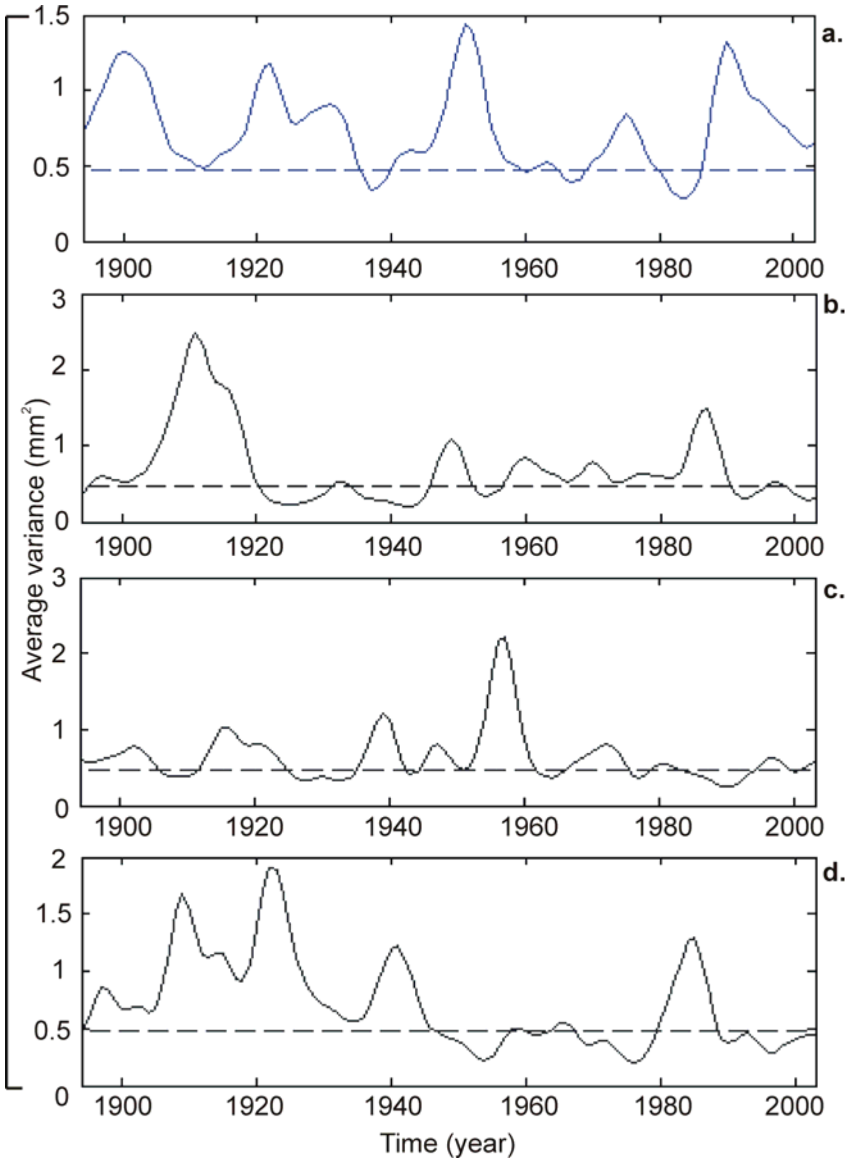

Figure 7: Time series of scale-averaged (2-10 yr) wavelet power spectrum for: (a) summer, (b) winter, (c) spring, and (d) autumn precipitation.

concentration of wavelet power in the 2-4 yr band between 1940 and 2000. High frequency oscillations appear weak prior to 1940. Unlike the annual precipitation, lower frequency oscillations (6-12 yr. cycles) are strong for summer precipitation, especially between 1894 and 1962. No decadal cycles are significant beyond 1960. Decade-scale cycles have been reported for summer precipitation in the Great Plains region of the

Table 2. Results of correlation between precipitation and the Pacific SST indices.

Precipitation	Niño 3	PDO
Annual	0.28*	0.38***
Summer	0.012	0.027
Spring	0.24*	0.27*
Winter	0.17	0.12
Autumn	0.19	0.30**

Entries are the Pearson correlation coefficients (r), (n = 100)
* Significant at $P \leq 0.05$; ** $P \leq 0.001$; *** $P \leq 0.0001$

United States (e.g., Ting and Wang, 1997; Hu et al., 1998). The CWT power spectrums for winter, spring, and autumn precipitation all show interannual cycles between time scales of 2-6 years. Please refer to Figure 7 for the temporal resolution of these cycles. No decadal oscillations are observed within these seasons. Comparatively, the power spectrum for spring precipitation bears close resemblance to that for annual precipitation, except for the absence of decade-scale cycles. This suggests that the spring precipitation contributes most to the observed high frequency oscillations in the annual precipitation for the study area. Such interpretation is reasonable because spring precipitation accounts for about 40% of the area's annual precipitation.

Thus, all four seasons show a common cycle interval of at least 2-4 years. The durations of these cycles are consistent with those reported for the Great Plains region as a whole (e.g., Barlow et al., 2001; Schubert et al., 2004; Ting and Wang, 1997).

Some studies have linked the variability in the Great Plains precipitation to variability in the Pacific SST, associated with the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). For example, Schubert et al., (2004) associated increased (decreased) precipitation over the Great Plains with ENSO conditions (positive or negative phases) in the tropical North Pacific. Similarly, Seager et al., (2005) showed that low-frequency precipitation for the Great Plains is correlated significantly with the Niño 3 index. Trenberth and Branstator (1992) found a similar correlation on the year-to-year time scale. To investigate these teleconnection influences on northwestern Oklahoma precipitation specifically, we correlated annual and seasonal precipitation for the region with the ENSO (NIÑO 3) and PDO indices. Table 2 summarizes results of the correlation analyses. It shows that annual precipitation is correlated significantly both with the Niño 3 ($P \leq 0.05$) and the PDO ($P \leq 0.0001$) indices but a stronger association with the PDO ($r = 0.38$ vs. 0.28, $n = 100$). Within the seasons, spring precipitation is significantly ($P \leq 0.05$) correlated both with the Niño 3 and the PDO indices. A significant ($P \leq 0.001$) correlation is also found between precipitation in the autumn and the PDO index. These results are consistent with the studies cited above.

Streamflow. Figure 8 presents the normalized CWT power spectrums for annual streamflow in northwestern. The top panel of each figure is time-series plot of the raw data. Figure 8a is the power spectrum for annual streamflow at the Beaver gauging station on the Beaver River. Power concentration is observed within the 2-5 yr. band between 1942 and 1970. Beyond 1970, no significant wavelet activity is observed. The time-series plot (top panel) shows also a significant drop in flow magnitude from about 1974 to the end of the time-series. We attribute this change to the onset of significant anthropogenic impact that may have resulted in non-stationarity of the time-series. Wahl and Tortorelli (1996) attributed the changes in streamflow in northwestern Oklahoma to rapid groundwater extraction,

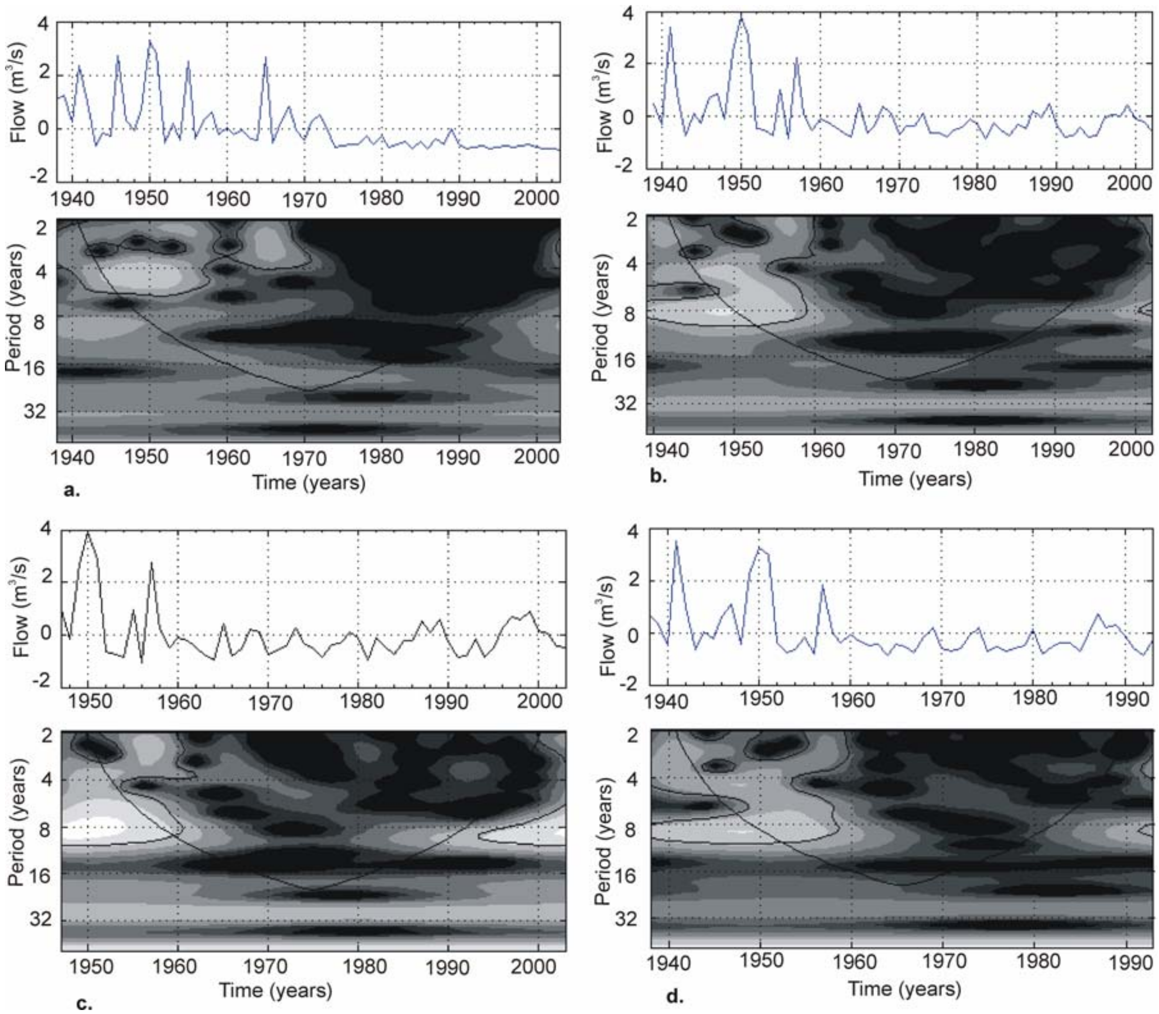

Figure 8: CWT power spectrum for annual streamflow at (a) Beaver; (b) Woodward; (c) Seiling; and (d) Canton.

which began with the introduction of the center-pivot sprinkler systems in the early 1960s. It is noteworthy that the CWT method appears to have successfully detected the anthropogenic impact on the natural cycle of streamflow variability. Downstream on the North Canadian River, the temporal pattern of power variability is very similar from station to station (Figures 8b-d). Common to all three stations is a spectral shift from interannual to decadal cycles that occurred between 1940 and 1960, and beyond 1990. Note that the exact magnitudes of the decadal oscillations may have been affected by the padding of the original series. Consistent also, with all four stations, is the low wavelet activity between the late 1960s and the 1980s. We speculate that land-use changes and land management practices also may have contributed to the observed low flows during this period. This is plausible because regional precipitation does not exhibit any obvious non-stationary behavior during the same period.

3.4 Conclusion

This study investigated trends and periodicities in the hydroclimatic time series for northwestern Oklahoma using the non-parametric Mann-Kendall trend test and continuous wavelet transform methods. It expands on previous efforts on hydroclimatic time-series analysis in northwestern Oklahoma by isolating also periodicities embedded in the hydroclimatic time-series, providing a more complete picture of the hydroclimatic dynamics within the study area. Statistically significant trends in precipitation were found at individual gauging stations and at different time scales but not in the regionally averaged annual precipitation. Similarly, no statistically significant trends were detected in the seasonal time-series. Trends were detected in the streamflow time-series with the Beaver River showing negative trends at all time scales. The declining streamflow is attributed to groundwater overdraft primarily because precipitation for the region remained largely stationary during the same time period. The CWT analysis isolated both interannual and decade-scale modes of precipitation and streamflow variability in the study area. The study also highlights the role of anthropogenic demands on the regional hydrologic system. Specifically, it suggests that anthropogenic impacts on streamflow in northwestern Oklahoma became significant around 1974. The study also indicates that precipitation in the study area is related to ENSO and PDO activity, again consistent with results reported elsewhere in the Great Plains region.

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Chapter 4

Simulating the Impacts of Groundwater Pumping on Stream-Aquifer Dynamics in Semiarid Northwestern Oklahoma, U.S.A.

SIMULATING THE IMPACTS OF GROUNDWATER PUMPING ON STREAM-AQUIFER DYNAMICS IN SEMIARID NORTHWESTERN OKLAHOMA, U.S.A.

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Abstract

This study utilizes Visual MODFLOW, a numerical groundwater flow model, to evaluate the impacts of groundwater exploitation on streamflow depletion in the alluvium and terrace aquifer of the Beaver-North Canadian River (BNCR) in northwestern Oklahoma. Water demand in the semi-arid Northwestern Oklahoma region is projected to increase by about 53% during the next 5 decades, driven primarily by irrigation and a burgeoning hog industry. Using MODFLOW's streamflow routing package, pumping-induced baseflow and stream leakage changes were analyzed to obtain total streamflow depletion for 9 different segments of the BNCR system. Simulation results indicate groundwater pumping has reduced baseflow to streams (29%) and increased stream leakage to the aquifer (18%). The magnitude and intensity of streamflow depletion, however, varies for different river segments, ranging from 0 to 20804 m^3/d. The density of well clusters and the intensity of water withdrawal appears to be major factors influencing stream depletion rates. The study provides a framework for isolating and quantifying the impacts of water withdrawal on streamflow depletion both spatially and in terms of water use sectors.

Keywords: Stream-aquifer interaction, numerical simulation, stream depletion, northwestern Oklahoma, MODFLOW.

4.1 Introduction

In arid and semiarid environments, alluvium and terrace deposits along streams often constitute shallow productive aquifers that support a variety of human activities. On the Great Plains of United states for example, alluvial aquifers are some of the most dependable sources of fresh water for irrigation, municipal, agricultural, and industrial uses (Adams and Bergman 1996; OWRB 1997; Ryder, 1996; Sherman et al. 1993). These aquifers also are critical to aquatic and wetland ecosystems because they recharge overlying streams during non-flood periods. From the point of view of water resources development, the superficial location of alluvial aquifers is appealing because exploitation costs are low relative to bedrock aquifers. This apparent advantage is, however, double-edged as low exploitation costs frequently invite overexploitation with serious adverse implications for water resources management. For example, groundwater pumping can intercept baseflow that would otherwise end up in the stream. Similarly, excessive pumping may reverse the hydraulic gradient between aquifer and stream, causing a stream that originally was gaining (affluent) to become a losing (effluent) one (Chen and Chen 2004; Nyholm et al. 2002; Osman and Bruen 2002; Wilson 1993). The resulting diminished flow downstream sometimes becomes a cause of conflict among competing users and stakeholders (see,Tarhule and Woo 1997).

There is a need, therefore, for understanding stream-aquifer dynamics in the context of anthropogenic water use. Such understanding can facilitate the development of conjunctive management programs that safeguard groundwater and surface water resources, as well as the socio-economic and ecological systems that depend upon them.

Groundwater simulation has emerged the tool of choice among water resources researchers and planners for addressing questions about the impacts of groundwater development, (Reilly 2001). The simulation approach attempts to replicate real-word complexity by integrating components of the physical hydrogeologic system, climatic effects, and anthropogenic stresses, thereby providing insight not only about changes within the aquifer but also their interactions with overlying surface water systems. Thus, when several scenarios are considered, the result obtained provides for water resources managers the means to evaluate and reconcile competing management alternatives (Senthilkumar and Elango, 2004).

Indeed, attempts to simulate groundwater-surface water interaction have a long history. Early studies, such as those by Theis (1941), Glover and Balmer (1954), and Jenkins (1968), provided analytical solutions to the stream-aquifer problem. Despite being groundbreaking, these solutions were based on somewhat idealistic assumptions, such as the requirement of fully penetrating streams and wells, and perfect hydraulic connectivity between aquifer and stream. Rarely, if ever, are such conditions obtained in a physical system. Subsequent and more realistic analytical solutions incorporated the effects of a clogging streambed layer whose hydraulic conductivity might be different from that of the underlying aquifer (Hunt 1999; Butler et al. 2001; Chen and Yin 2004; Zlotnik 2004). Even with such enhancements, analytical solutions still have a tendency to overestimate stream depletion (e.g. Sophocleous et al. 1995; Conrad and Beljin 1996). As a result, the numerical simulation approach is increasingly being applied to stream-aquifer investigations (e.g. Barlow et al. 2003; Chen and Yin, 2001; Chen and Shu, 2002; Rodriguez et al. 2006). Comparative studies (Sophocleous et al. 1995; Conrad and Beljin

1996) show that the numerical solution provides superior estimates of stream depletion relative to the analytical, because it represents more comprehensively complexities within the physical hydrogeologic system.

In this study, MODFLOW (McDonald and Harbaugh 1988), a 3-dimensional numerical groundwater flow model, is used to investigate the impacts of groundwater pumping from an alluvial aquifer on stream-aquifer interactions, specifically, streamflow depletion, in the semiarid but agriculturally important northwestern Oklahoma.

4.2 Study Area and Hydrogeologic Setting

The study area is the 2150 km^2 alluvium and terrace (A&T, for brevity) aquifer of the Beaver-North Canadian River (BNCR) in northwestern Oklahoma (Figure 1). The regional climatic setting is semi-arid with mean annual precipitation of approximately 664 mm. About 83% of the precipitation falls between the months of March and October; however, May and June receive the largest amounts of the total precipitation (16% and 13% respectively). Additionally, year-to-year precipitation variability is high with a coefficient of variability of about 19%. Consequently, the region is drought-prone, even without the complicating effects of anthropogenic water withdrawals.

The surface drainage network is sparse and characterized by high evaporative losses, between 1422 and 1626 mm on average, or about 230% of annual precipitation (OWRB 1997). The Beaver and the North Canadian Rivers, along with their tributaries, drain the study area. The Beaver River enters Oklahoma from New Mexico and flows southeasterly through the study area, becoming the headwaters of the North Canadian at its confluence with Wolf Creek (see Figure 1). The North Canadian River continues the southeasterly course across central Oklahoma to empty into the Arkansas River to the east.

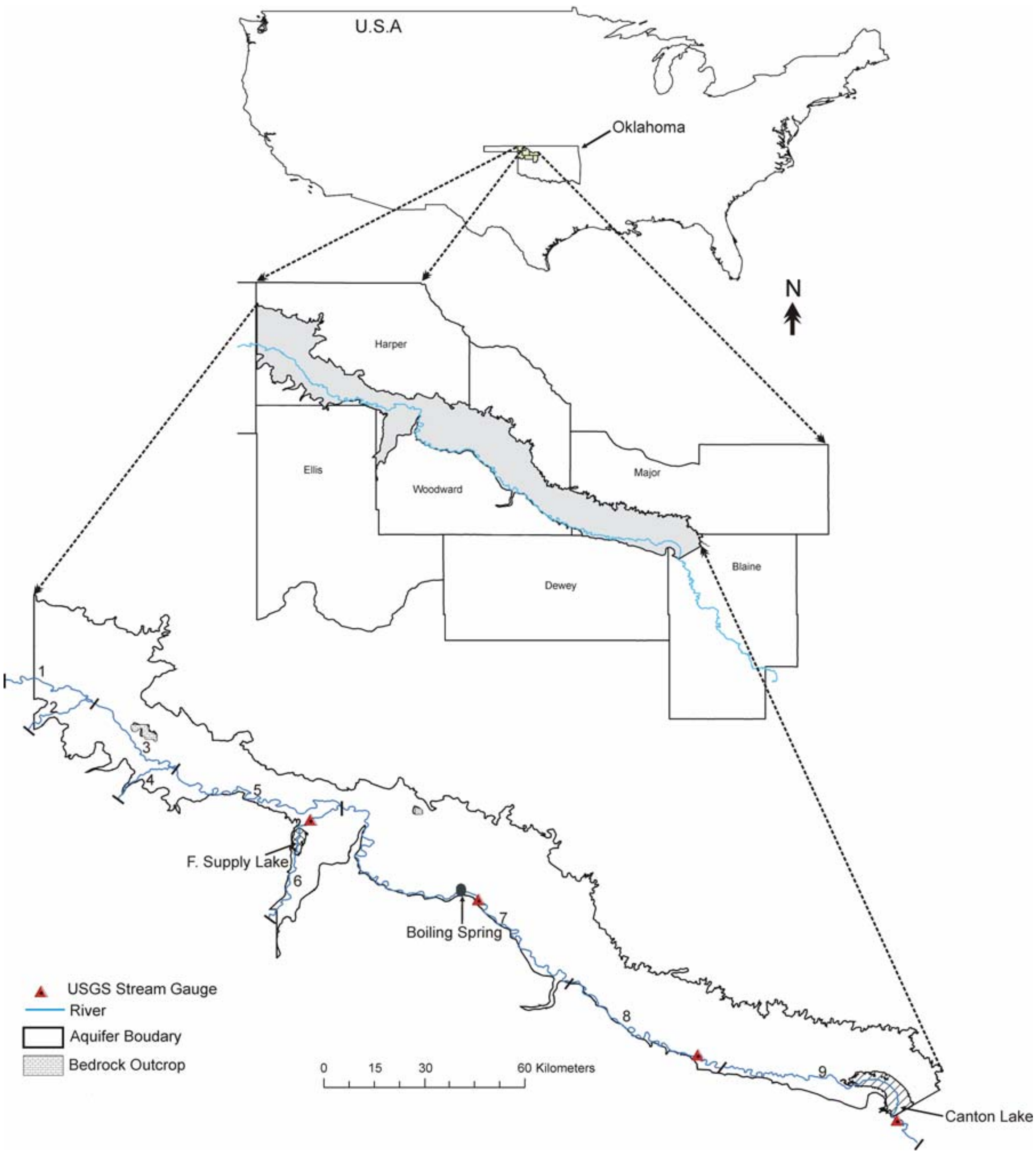

Figure 1: Location of Study Area

Within the study area, Davis and Christenson (1981), coined the term “Beaver-North Canadian River” to represent the combined river channels of the Beaver and the North Canadian. This term is adopted for this study.

Geologically, the A&T aquifer is composed primarily of Quaternary deposits, which occur mainly north of the BNCR (Davis and Christenson 1981). These deposits are oriented concordantly relative to the river, the result, most likely, of the river’s southerly migration down the regional dip of the underlying red beds formation, and the influence of dominant southerly winds. The Quaternary deposits consist of four geologic units: the high and low terrace deposits, the alluvium, and the dune sands. The thicknesses of these deposits vary spatially. The high terrace deposits, for example, average about 21 m thick, compared to 10 m for the alluvium. The terrace and alluvium deposits are the principal water-bearing units. They comprise of poorly sorted, fine to coarse-grained, unconsolidated quartz sand, containing minor amounts of clay, silt, and basal gravel (Davis and Christenson, 1981). It is believed that the alluvium and terrace deposits are hydraulically connected and constitute a single aquifer unit that is generally unconfined. Information from drillers’ logs supplied by the Oklahoma Water Resources Board (www.owrb.ok.gov/wd/search/search.php) suggests the base of the aquifer in most locations is the top of the Permian red beds Formation. The red beds are relatively impermeable and act as a barrier to vertical water leakage from the aquifer. Depth to bedrock varies spatially with a maximum of about 100 m. At a few locations however, the bedrock outcrops at the surface. The Tertiary Ogallala and the Rush springs formations underlie the aquifer in the northwestern corner.

Intensive exploitation of the A&T aquifer began during the early 1960s with the introduction of center-pivot sprinkler irrigation in parts of the area (Wahl and Tortorelli, 1996). More recently, a burgeoning hog-farming industry has increased aquifer water use significantly. As a result, the Oklahoma Water Resources Board (OWRB) projects that regional water demand will increase by about 53% over the 1990 levels by 2050 (OWRB 1997). Such level of aquifer use can be expected to impact stream-aquifer interactions and may have implications also for regional water resources planning. To date however, the only major study of the aquifer was carried out by Davis and Christenson (1981), who investigated the impacts of aquifer pumping on groundwater levels using a 2-dimensional numerical groundwater model. The authors concluded that stressing the aquifer over a forty-year period (1978-2020) at the 1977 pumping rates and well distribution would decrease its saturated thickness by about 0.5 m on average. However, the authors did not investigate the possible impact of aquifer pumping on stream aquifer interactions. This is the focus of the present study.

4.3 Model Development

This study was carried out using Visual MODFLOW (VM) pro. version 4.1, a proprietary product of Waterloo Hydrogeologic Inc. (2005). VM (4.1) has enhanced capabilities for pre- and post- processing input and output data for the well- established U.S. Geological Survey (USGS) groundwater flow code, MODFLOW (McDonald and Harbaugh 1988).
MODFLOW has been applied extensively for simulating groundwater dynamics, including surface water/groundwater relations (e.g. Chen and Chen 2004; Senthilkumar

and Elango 2004; Varni and Usunoff 1999; Wilsnack et al. 2001; Fleckenstein et al. 2006).

In this study, the A&T aquifer was discretized into a finite-difference grid of 43,384 cells, comprising 187 rows and 232 columns oriented in the direction of regional groundwater flow. Cell sizes were set at 0.35 km per side, except for cells containing pumping wells and stream reaches, which were further refined to capture local changes in the hydraulic head and stream-aquifer fluxes. The model was vertically discretized into three layers to enhance its ability to calculate heads in the vertical direction. The discretization was done with consideration of the hydrogeologic framework described earlier. Aquifer top elevations were derived from a digital elevation model, while layer elevations were determined on the basis of well-completion reports and logs contained in the OWRB database (www.owrb.state.ok.us/wd/search/search.php).

The model simulated several boundaries. As required by MODFLOW, the active area of the model was surrounded by no-flow boundaries. The aquifer base also was treated as a no-flow boundary, consistent with the regional bedrock geology. Two reservoirs, Fort Supply and Canton Lakes, located within the model domain, were represented by constant head cells. The Tulsa district of the U.S. Army Corps of Engineers (www.swt-wc.usace.army.mil) provided the stage data for the lakes. Subsurface inflow to the aquifer from the upstream end, and outflow at the downstream end, were simulated with general head boundaries. Alluvial deposits extend beyond the geographic limits of the study area at both ends. Consequently, drain cells were used to simulate leakage from the aquifer to the adjacent Cimarron alluvium on the northeastern corner of the study area. Similarly, aquifer discharge through the main spring at Boiling

Springs Park was simulated with drain cells. Spring discharge obtained from the Park's office was 164 m^3/day. In both cases, drain conductances were first assigned arbitrarily and then modified during model calibration. Subsurface inflow to the aquifer from the Ogallala formation around the southwestern part of Harper County was represented by constant flux nodes using the recharge package.

Direct precipitation recharge to the aquifer was assumed to be 10% of annual precipitation. Thus, consistent with the range in annual precipitation, the recharge varied from 6.96×10^{-5} m/day in the western part of the aquifer to 1.39×10^{-4} m/d in the southern part, with an average of 1.03×10^{-4} m/d. Irrigation return flow was assumed to be 20% of annual irrigation pumpage (e.g. Davis and Christenson, 1981). This amount was not added explicitly as recharge in the model. Instead, reported withdrawal at each irrigation well was reduced by 20% to account for the return flow. This approach avoids assigning higher recharge values to areas without irrigation wells. Groundwater evapotranspiration (E_p) was not simulated in the model because the area contributing E_p is less than 1% of the model domain. Groundwater withdrawal (an internal boundary) was specified in the model at 131 nodes representing actual locations of pumping wells. Annual pumping rates at each well were based on water use reports submitted annually to the Oklahoma water resources Board by permit holders.

Stream-aquifer interactions were simulated with the streamflow routing package developed for MODFLOW by Prudic (1989). Conceptually similar to the river package in MODFLOW, the streamflow routing package has the additional capability to track the amount of water in each simulated stream segment. Stream stage was computed iteratively using Manning's roughness coefficient. This approach is superior to that used in the river package where river stage must be kept constant for each stress period. Simulations were performed for both steady and non-steady state conditions. The BNCR and its tributaries were simulated as head-dependent flux boundaries. All rivers were simulated as partially penetrating with leaky riverbeds. The river system was divided into a total of nine segments (refer to Figure 1). The main river (Beaver-North Canadian) comprised six segments, while the remaining three were tributaries. Along a river segment, each model cell constitutes a river reach; hence, the nine river segments consisted of a total of 502 reaches. For each river segment, digital data, including average flows and channel characteristics (e.g. stage, slope, width, and Manning's roughness coefficient) were obtained from the US EPA's BASINS program (version 3.1). The BASINS program is a multi-purpose environmental analysis system that integrates a geographic information science (GIS), national watershed data, and other environmental assessment and modeling tools into a single package. The program is available for free download at www.epa.gov/waterscience/basins. Within the BASINS program is the Reach File (RF1) package containing a database of approximately 1,126,300 km of streams with related hydrologic data for the conterminous United States. The RF1 package was queried for specific data on the BNCR watershed. Additionally, stream discharge for four of the nine simulated river segments were obtained from USGS gauges (www.waterdata.usgs.gov/ok/nwis)

The streamflow routing package calculates the flow between each stream reach and the corresponding aquifer cell using equation (1) (Prudic, 1989):

$$Q_L = C_s(h_s - h_a) \qquad (1)$$

where

Q_L is the flow between the stream reach and the aquifer (m^3/d);

C_s is the streambed hydraulic conductance (m^2/d);

h_s is the hydraulic head in the stream reach (m);

h_a is the hydraulic head in the aquifer underlying the stream reach (m).

Whether groundwater discharges to the stream or vice versa, depends on the direction of the slope between the respective hydraulic heads.

The conductance term in (1) is calculated as (Prudic, 1989);

$$C_s = \frac{KwL}{M} \qquad (2)$$

where

K is the hydraulic conductivity of the streambed material in the reach (m/d);

w is the width of the stream reach (m);

L is the length of the stream reach (m);

M is the thickness of the streambed material (m).

Equation (1) holds when there is saturated hydraulic connection between the river and the aquifer. When the river is dry, i.e. h_a falls below the streambed bottom elevation (h_{bot}), then Q_L is calculated as:

$$Q_L = C_s(h_s - h_{bot}) \qquad (3)$$

For each segment, streamflow must be specified for the first reach, the program then calculates and routes flow to adjacent downstream reaches after adjusting for the stream-aquifer fluxes.

The input parameters required for each stream segment, including width and discharge were specified. Stream widths were obtained from the RF1 package discussed previously. Certain parameters (e.g. streambed hydraulic conductivities and thicknesses) for which data were not available, assumed values were used initially and modified during model calibration. For example, a uniform streambed hydraulic conductivity of 0.3 m/d (approximately 1% of the average aquifer hydraulic conductivity) was assigned to all stream segments. Similarly, for each stream segment, the thickness of the bed materials was assumed: values for all segments ranged from 0.3 to 1.5 m depending on segment width and depth.

4.4 Model calibration

The model was calibrated to both quasi-steady-state (QSS) and transient conditions. The term QSS denotes the fact that groundwater exploitation within the aquifer began long before the period used for the steady-state calibration. However, average groundwater levels and streamflow conditions for the QSS period approximate reasonably long-term steady-state conditions in the basin (e.g. Davis and Christenson 1981). The QSS calibration was needed to provide the basis for isolating pumping-induced stream-aquifer fluxes. Additionally, it provided initial conditions for transient simulations. No pumping was introduced during the QSS simulation.

The QSS calibration was achieved by matching calculated hydraulic heads and average groundwater level elevations in observation wells. Similarly, calculated baseflows were matched with average baseflows separated from observed streamflow records at four USGS streamflow gauging sites in the study area. Simulated heads were compared with observed average conditions for December-March of 1978-79. The automatic parameter estimation program, PEST (Doherty 2001), was used for the calibration. PEST automatically adjusts model parameters until the fit between model outputs and observations is optimized. The process calculates also the sensitivity of each parameter to model results.

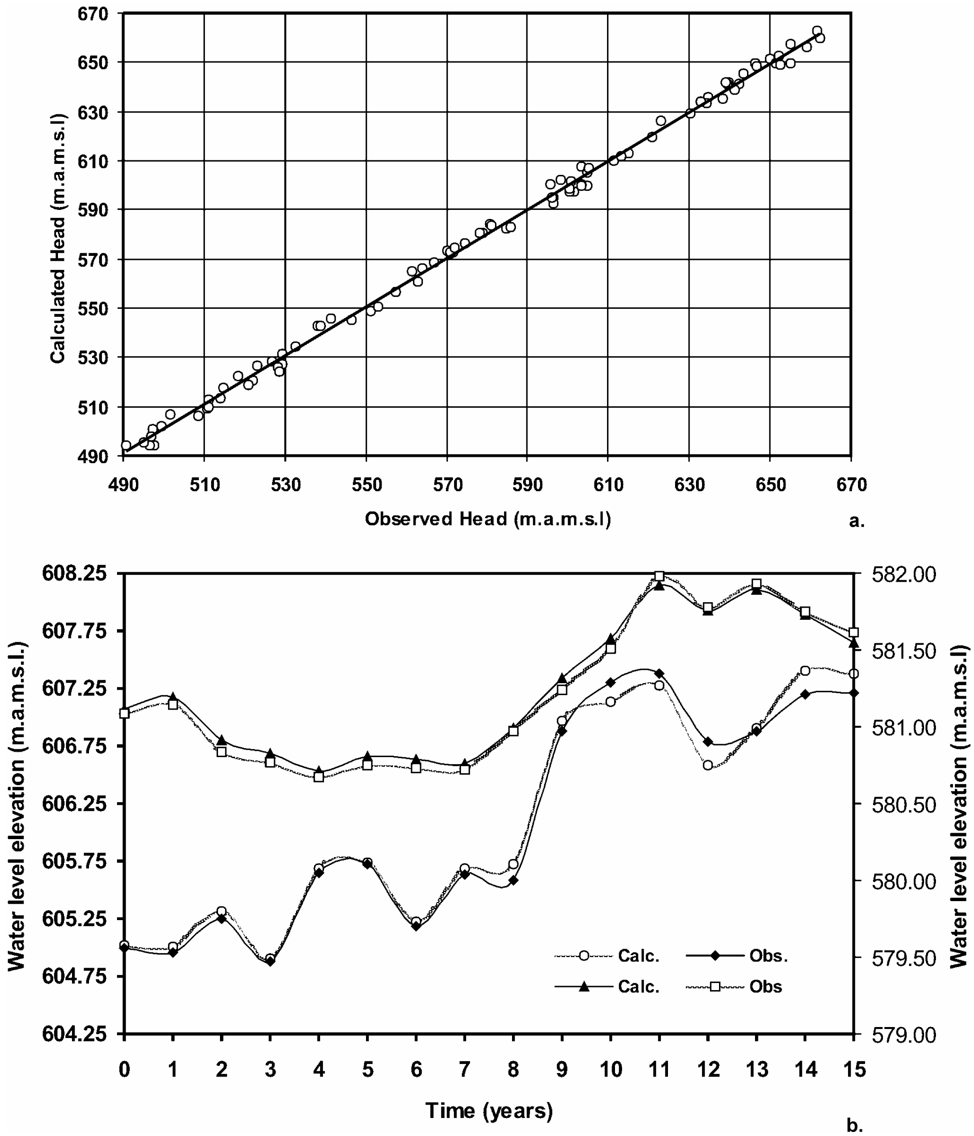

Figure 2: (a) Calculated vs. observed heads for the QSS calibration (b) Calculated vs. observed groundwater hydrographs for the transient calibration.

Parameters modified during the calibration process include hydraulic conductivity (K), streambed and drain conductances, Manning's roughness coefficient (*n*), and recharge. Initial estimates for K and *n* were derived from existing site information while the streambed and drain conductances were assumed because no prior information existed for them. Calibrated K values for the aquifer ranged from 0.78 to 65 m/d, with an average of 30.81 m/d. The value of K at the low end is consistent with that reported by Davis and Christenson (1981) for the aquifer, but the upper limit is significantly higher than their results (65 vs. 49 m/d). However, Wood and Statcey (1965) reported K values of up to 61 m/d from six pumping tests within the aquifer, which is reasonably close to the upper value of K obtained for this study. Overall, simulated heads matched groundwater level elevations measured in 91observation wells across the aquifer satisfactorily. 29% of the observation points had residuals between 0 and ±1.5 m, 47% between ±1.5 and 2.5 m, and 20% between ±2.5 and 3.5 m. Only 4% had residuals greater than 3.5 m. The mean of the absolute residual (MAR) was 2.34 m, well within the error range of the digital elevation model (DEM) used to derive water level elevations and the water level measurement themselves. Figure 2a shows the calculated vs. observed calibration graph.

Next, recharge, streambed conductances, and Manning's roughness coefficients (*n*), were adjusted until simulated and observed streamflows and baseflows also matched satisfactorily. Calibrated streambed conductances ranged from 63 to 6038 m^2/d for the stream segments, while Manning's *n* values ranged from 0.045 to 0.06. Sensitivity analysis showed however, that model results respond only mildly to streambed conductances.

Calibration of the transient model was achieved by trial-and-error. The transient simulation spanned a 15-year period (1979-1994). Initial conditions for the transient simulation were those from the QSS calibration. Groundwater pumping was introduced over a single stress period, divided into 30 time steps with a minimum time step of 4.6 days and a maximum of 5475 days. Pumping rates at each well were averaged over the stress period. These vary from 73 to 6393 m^3/d. Calibration was achieved by adjusting the specific yield (S_y) until simulated heads matched annually observed groundwater levels in observation wells. Similarly, fine-tuning of the streambed characteristics was done, where necessary, to match simulated stream stages with those observed at four gauging stations for the same period. A final S_y value of 0.28 provided the best match between model output and observation. This compares favorably with a value of 0.29 reported by Davis and Christenson (1981) for the same aquifer. Figure 2b illustrates the excellent agreement between simulated and observed groundwater levels for two representative observation wells.

4.5 Model Runs

The calibrated model was used to estimate pumping-induced streamflow depletion, resulting from reduced baseflow and increased stream leakage. To assess changes in baseflow and stream leakage, a base transient simulation was performed with all pumping wells turned off. Stream-aquifer fluxes from subsequent transient runs (with pumping introduced) were compared with those for the base simulation. The resulting differences constituted the stream depletion rates.

Three more transient simulations were performed. The first was a simulation in which all wells located in the aquifer were pumped for a 15-yr period (1979-1994). The withdrawal rate at each well was the average of annual withdrawal rates over the 15-yr period. In the second simulation, only irrigation wells in the aquifer were pumped. Irrigation wells constitute 70% of all the wells included in the model, and account for nearly 90% of total aquifer withdrawal. It was, therefore, necessary to assess the relative significance of irrigation withdrawal on stream-aquifer dynamics. Finally, a simulation involving only non-irrigation wells was performed. Figure 3a shows the distribution of pumping wells within the A&T aquifer. Shown in Figure 3b are the nine simulated stream segments. Recall that the simulated stream system was fragmented into segments in order to capture stream-aquifer dynamics at finer scales.

4.6 Results and discussion

4.6.1 *Quasi-steady-state (QSS)*

The calibrated QSS model indicates direct precipitation recharge is the major input to the simulated stream-aquifer system (66%), while stream leakage accounts for 30% of aquifer recharge. Other sources of recharge to the aquifer include subsurface seepages from adjacent groundwater basins (3%) and from lakes (1%). On the output side, groundwater discharge to streams (baseflow) is the largest outflow component (56%) from the aquifer. Groundwater also exits the aquifer into lakes (32%), adjacent groundwater basins (11%), and through Boiling Spring (<1%). These results are consistent with those reported by Davis and Christenson (1981), and other studies for alluvial aquifers in western Oklahoma (e.g. Adams et al. 1996). The results confirm that

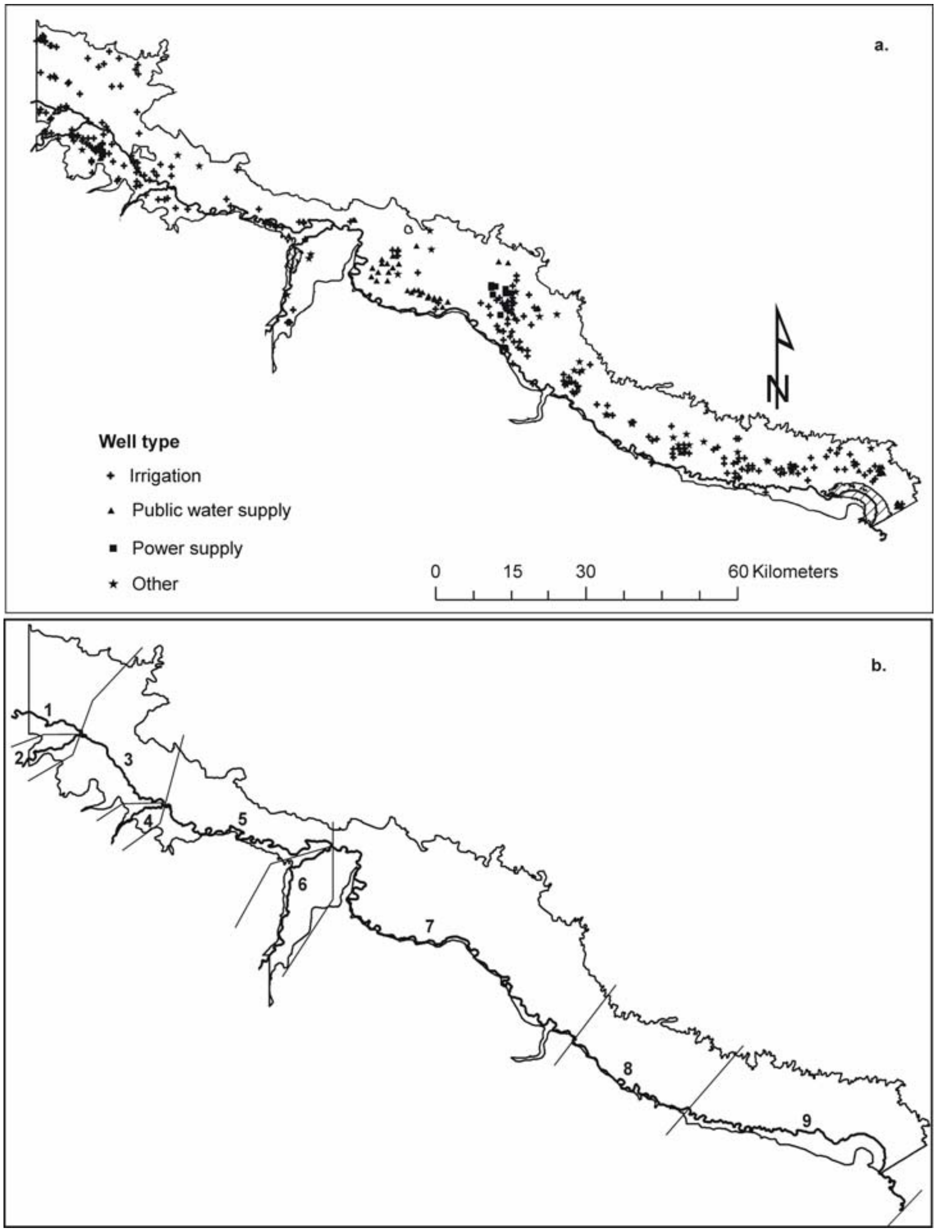

Figure 3: Aquifer map showing (a) the distribution of pumping wells, (b) simulated stream segments. Each segment is shown numbered.

both natural climatic variability that alters the amount of precipitation input to the basin, as well as anthropogenic groundwater pumping that alters streamflow/groundwater levels, can be expected to have major impacts on stream-aquifer dynamics in the study area.

Calibrated QSS fluxes across the streambed (stream-aquifer interaction) were assed for each stream reach using the zone budget feature in MODFLOW. The zone budget program uses the simulated cell by cell flux terms to calculate sub-regional budgets for any user-defined zones within the model domain. Figure 4 summarizes the QSS-derived stream-aquifer interaction for the designated stream segments. The top panel (4a) shows fluxes across the streambed at individual reaches of the nine stream segments. A positive flux indicates stream leakage (i.e. flow from the stream reach to the aquifer) while a negative one represents baseflow from the aquifer to the stream reach. The bottom panel (Fig. 4b) shows total baseflow and stream leakage for all reaches within each stream segment.

Figure 4a shows that while nearly all segments of the BNCR system have both effluent (gaining) and influent (losing) reaches in varying degrees approximately 79% of all reaches are effluent. Thus, the stream, overall, is considered a gaining one. In general, stream-aquifer fluxes are controlled primarily by the aquifer-stream hydraulic head gradient, as well as the hydraulic properties of the streambed material, which may vary spatially and temporally. Other relevant factors include dynamics associated with abrupt changes in the streambed slope or meanders in the stream channel (Winter et al. 1998). For these reasons, it is not uncommon, to have influent stream reaches even in a strong gaining system like the BNCR system. For example, Figure 4 shows that segment 3 is strictly effluent, 4 is strictly influent, and the entire stream leakage in segment 9 comes from reaches within the last one-third of the segment. These results are consistent with

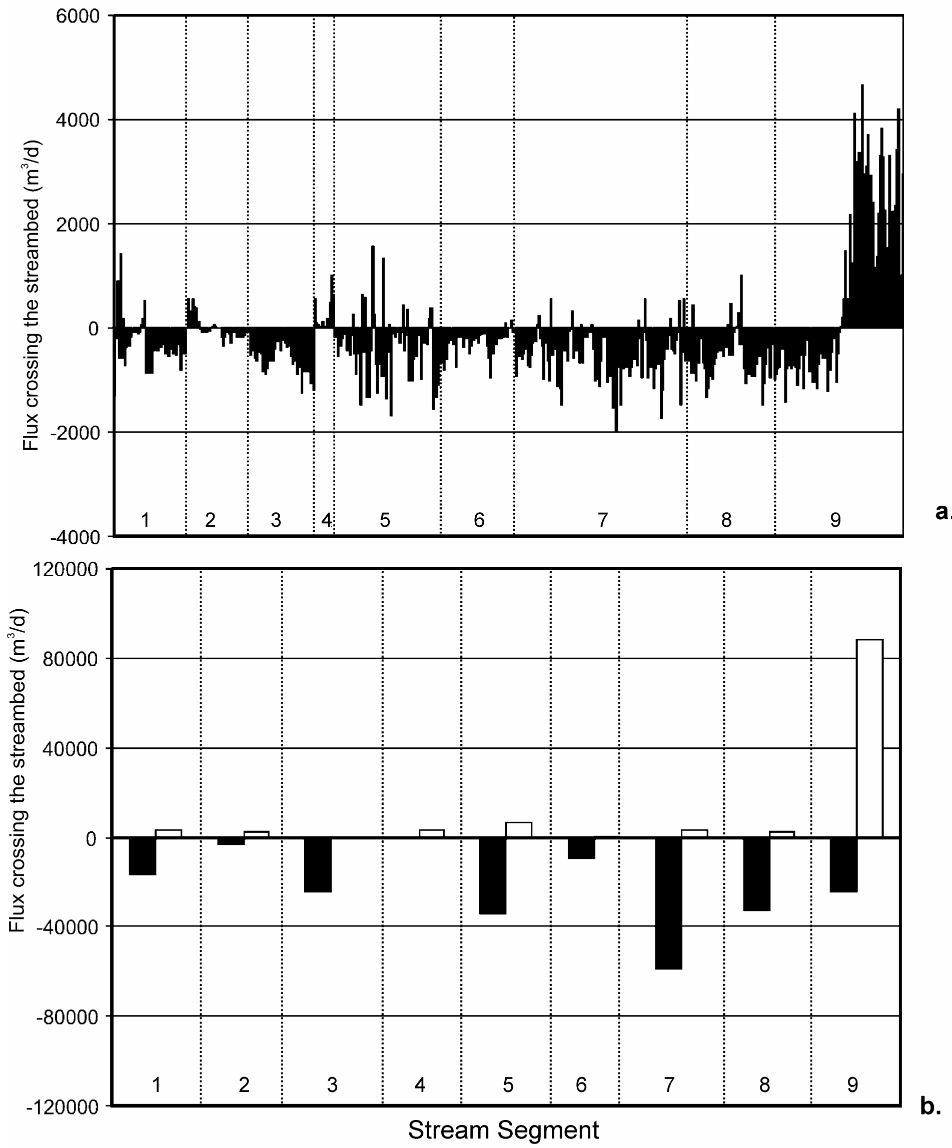

Figure 4: QSS stream-aquifer fluxes (a) at individual stream reaches, (b) sum of reach fluxes per segment. Positive flux is stream leakage into the aquifer, negative flux is aquifer discharge to stream (baseflow).

the physical hydrogeologic setting. Located on the Beaver River, segment 3 receives baseflow contributions throughout the year, hence it is gaining. On the other hand, segment 4 (an influent segment) is a small, seasonal, tributary stream and therefore prone to leak water to the aquifer. Finally, located just south of Lake Canton (refer to Fig. 3b), the last one third of segment 9 accounts for over 80% of total leakage from the stream system. This is because at this location, lake releases maintain high stream stages even during periods of low flow, providing suitable hydraulic gradient for stream discharge to the aquifer.

It is known generally that perennial rivers are sustained by baseflow. Therefore, the significance of the results above lies in the fact that it disaggregates the stream system into finer spatial scales (segments) and provides insight into the dynamics of stream-aquifer interactions within each individual segment. Though outside the scope of the present work, the information obtained could be used, in principle, to site wells in a manner that does not compromise the aquifer's ability to support streamflow. Even more important, the results could be used to determine gross, safe aquifer exploitation volumes based on desirable baseflow levels for aquatic, ecological, and other uses. Such analysis could be accomplished by first specifying the desired streamflow level and then back-calculating the maximum aquifer withdrawal that does not upset the pre-defined streamflow.

4.6.2 *Pumping-induced stream-aquifer relations*

4.6.2a *Effects of pumping all wells within the aquifer*

Prior to groundwater pumping, 56% of groundwater from the A&T aquifer discharged to the Beaver-North Canadian River (BNCR) network as baseflow, while 30% of stream leakage recharged the aquifer (refer to the QSS results). Results of the transient simulations, integrated over the entire stream system, indicate fifteen years of groundwater pumping has adversely impacted streamflow in the BNCR system by reducing baseflow to the streams and simultaneously increasing stream leakage into the aquifer. Figure 5 shows the percentage reductions in baseflow and induced stream leakage as a result of pumping all wells located in the aquifer over the 15-yr model period.

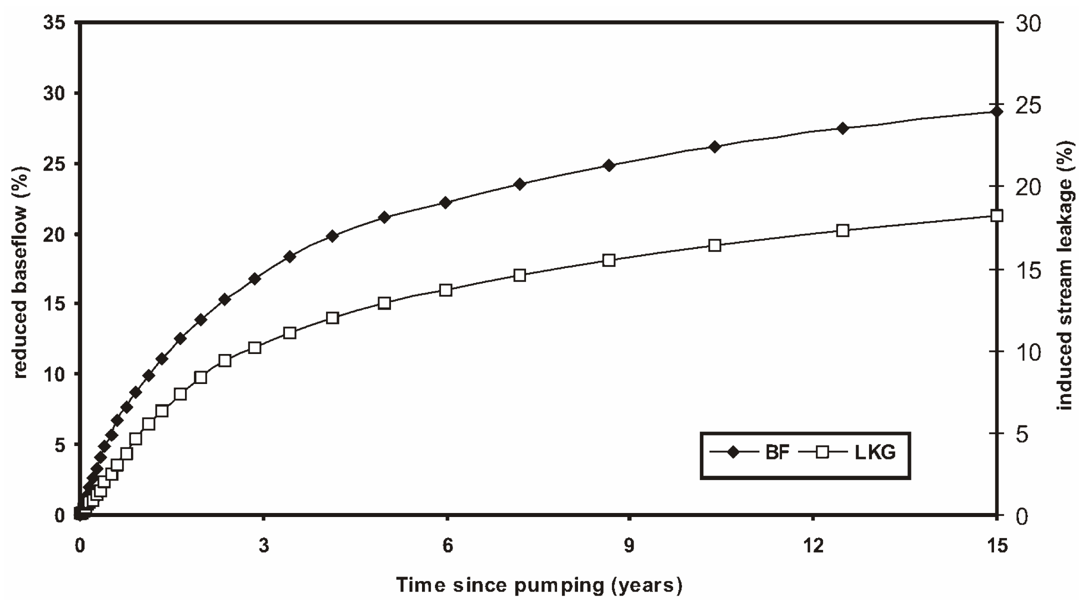

Figure 5: Percentage reduced baseflow and induced stream leakage.

Compared to the background (i.e. non-pumping) stream-aquifer fluxes, baseflow declined rapidly reaching 20% in the first 5 years and a total of 29% at the end of the 15th year of pumping. Similarly, pumping-induced stream leakage increased by 18% after the aquifer is pumped for 15 years. The monotonic decrease in these two components of streamflow is plausible given that both pumping and hydrogeologic parameters remained constant over the model stress period. Note that these results are averaged conditions over the entire stream-aquifer system. Results for the designated stream segments are discussed in the next section. At the scale of the entire stream-aquifer system approximately 63% of the total streamflow depletion is from reduced baseflow.

4.6.2b *Stream segment response to pumping all wells in the aquifer*

Figure 6(a-c) shows respectively, the rates of reduced baseflow (RBF), induced stream leakage (ISL), and the resulting total stream depletion (TSD; i.e. RBF+ISL) in the designated stream segments. RBF and ISL rates were determined as the difference at each model time step between a transient model without pumping and one with pumping introduced. (e.g. Chen and Yin 2001).

The results indicate that different stream segments respond differently to aquifer pumping. For example, stream depletion, resulting from the combined impacts of reduced baseflow and induced stream leakage, is higher in segments 5, 1, and 3 (in that order). On the other end, segments 4 and 6 show the least response to pumping. Notice in Figure 6c that in all segments, and nearly at all times of pumping, 'reduced baseflow' contributes most to the total streamflow depletion signature obtained. This is expected for most strongly gaining stream systems (e.g. Chen, 2003).

Close examination of Figure 6 also reveals differences in the temporal response of the stream segments to pumping. For example, after 120 days of pumping, significant flow depletion occurred to varying degrees in six segments but the remaining three (segments 3, 4, and 8) showed hardly any response. After one year of pumping however, all but one segment (segment 3) showed significant stream depletion. Additionally, the magnitude of depletion at this time scale, on average, is more than doubled (113%) that observed after 120 days of pumping. By the end of the third pumping year, streamflow

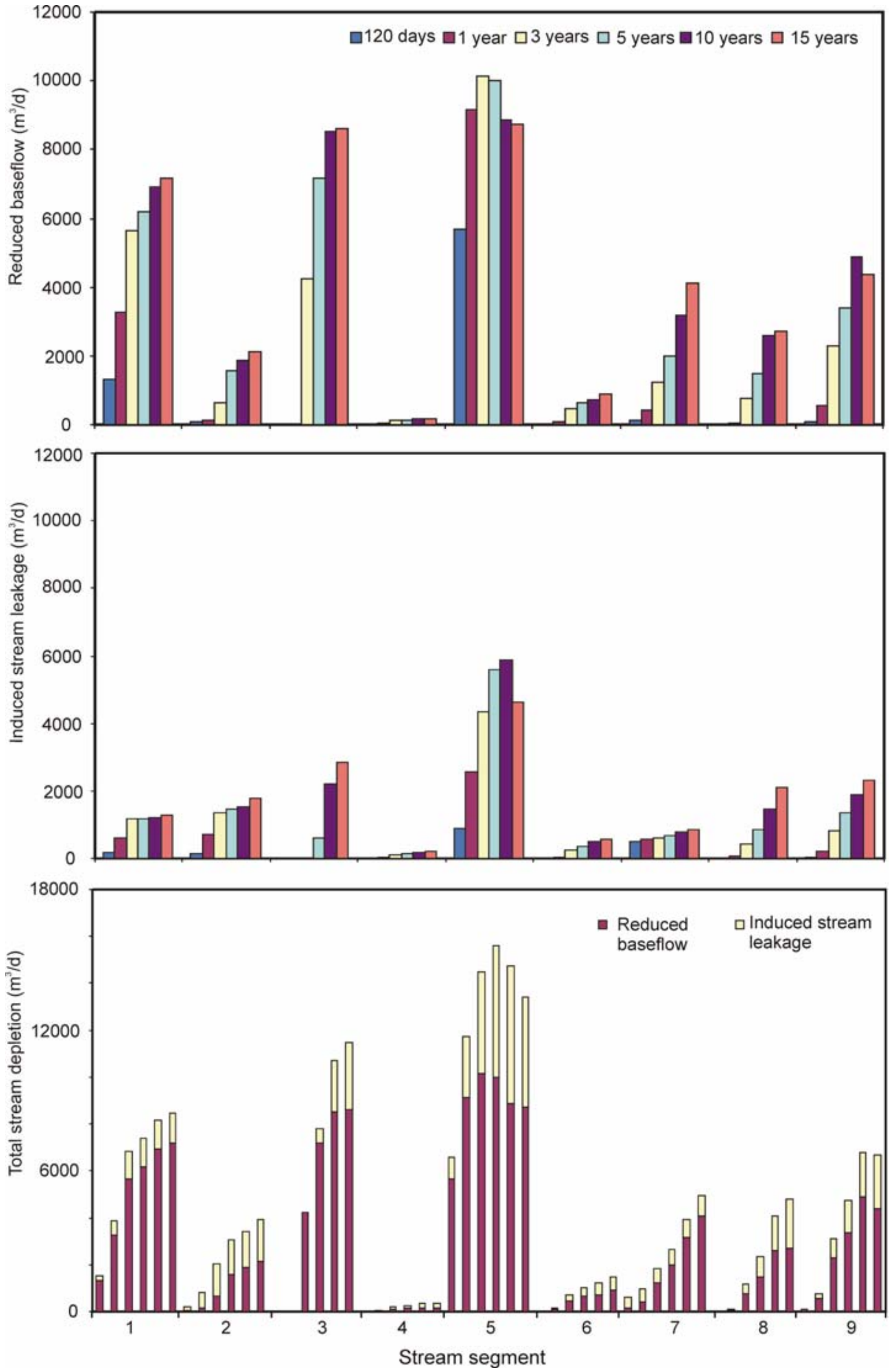

Figure 6: Stream depletion by segment (a) reduced baseflow, (b) induced stream leakage, (c) Total stream depletion. Results are for pumping all wells in the aquifer. Times shown are the lengths of pumping.

had declined in all stream segments. In general, stream depletion rates increased monotonically as pumping time increased. This is expected because as pumping time progresses, cones of depression develop around pumping wells and propagate their capture zones radially outwards, intercepting more baseflow. Where wells occur in close proximity to the stream channel, the expanding cones of depression may eventually reverse the hydraulic gradient between the stream and the aquifer, inducing also higher stream leakage into the aquifer. Notice however, in segment 5, the reduction in stream depletion with time after the first 3 years of pumping, and in segment 9, after the 10th year. This is strange, especially given that both the pumping rates and the hydrogeologic parameters remained unchanged over the model stress period. The cause of this anomaly is unclear at the moment but it could be speculated that the drying up of some stream cells within the affected segments may have reduced the total amount of flow available for depletion, hence, the anomalous behavior.

Stream depletion rate depends on several factors, including local streambed and channel heterogeneities, geology, as well as pumping-related dynamics (e.g. well-capacity or withdrawal volume, pumping duration, well density and proximity to stream channel) (e.g. Fleckenstein et al 2006; Chen and Yin 2001; Sophocleous et al 1988). A rigorous analysis of the relative significance of the above factors is beyond the scope of the present investigation. Even so, it seems apparent that stream depletion is influenced predominantly by the intensity and duration of groundwater pumping. For example, segments 1, 3, and 5, which have the highest magnitudes of stream depletion, also have the highest average water withdrawals per well (see Table 1). In contrast, with the fewest number of pumping wells around them (refer to Fig. 3a) segments 4 and 6 responded least to pumping. It is important to emphasize however that these observations must be interpreted cautiously. Frequently, well density and intensity of water withdrawal are themselves functions of hydrogeology or anthropogenic requirement. For example, the low well density in segment 6 is likely due to limited saturated thickness beneath the area (Davis and Christenson 1981). Additionally, segments 1, 2, 5, 7, and 9, which responded also to early pumping activity (120 days), all have several well clusters in close proximity (<500 m) to the stream channel.

Table 1: Number of wells and withdrawal per stream segment with corresponding average stream depletions.

Stream segment	**No. of wells**	**Total withdrawal (m^3/d)**	**Average Withdrawal per well (m^3/d)**	**Average depletion (m^3/d)**
1	37	54231	1466	6027
2	12	16481	1373	1778
3	63	52578	835	5708
4	3	2193	731	215
5	23	43753	1902	14811
6	8	2118	265	400
7	114	82482	724	2495
8	40	15139	378	1283
9	73	32891	451	2780

The above results suggest that sustainable aquifer management must take into consideration the various pumping factors that affect stream-aquifer interaction. For example, defining a safe range of well proximity to stream channels can reduce the vulnerability of stream segments to depletion. However, with unregulated large withdrawal volumes or prolonged pumping, even distant wells can adversely impact streamflow. One way of achieving optimum groundwater/surface water management is through a conjunctive management approach, which allows balanced exploitation of both sources.

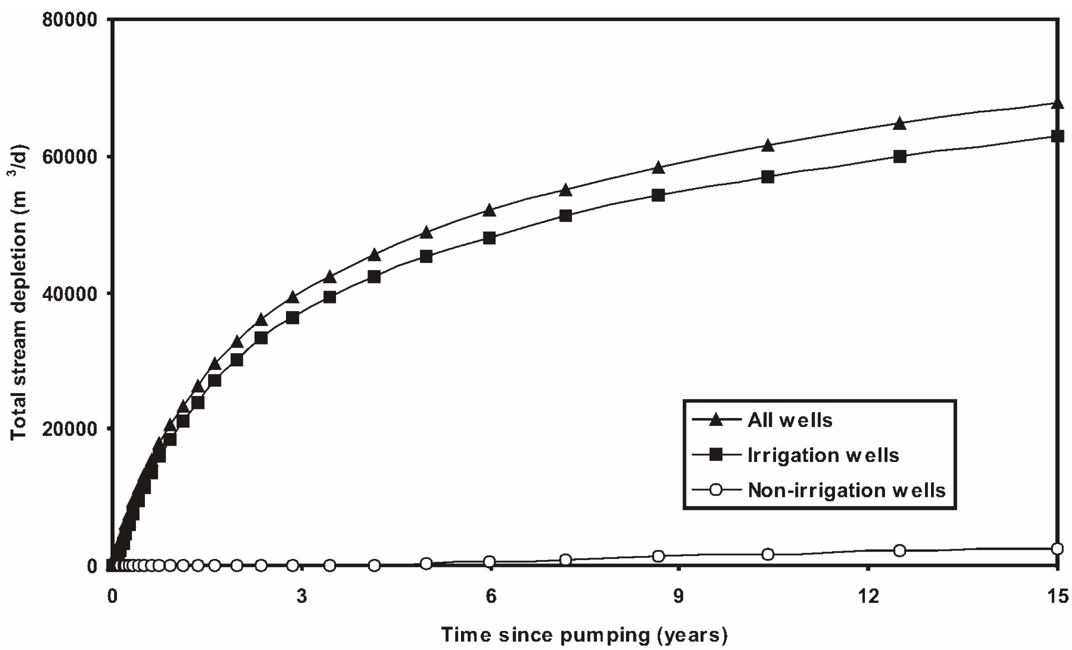

Figure 7: Comparative stream depletion caused by pumping "all wells", "irrigation wells", and "non-irrigation wells".

4.6.3 *Effects of irrigation and non-irrigation wells*

The pattern of stream depletion across stream segments, simulated by pumping irrigation wells only, is, largely similar to that obtained by pumping all wells within the aquifer (refer to Figure 6). There are differences however, in segments 7 through 9, which have significant numbers of non-irrigation wells (refer to Figure 3a). In segment 7 for example, the stream depletion rate is lower by 16% when only irrigation wells are pumped. Similarly, the depletions are lower by 11% and 1% respectively, in segments 8 and 9. Other than these, the rest of the segments generally show differences of less than 1%. The simulation involving only non-irrigation wells supports these observations.

Figure 7 compares the stream depletion rates for the three cases simulated; model runs with “all aquifer wells”, “irrigation wells”, and “non-irrigation wells”. Notice the close match between the “all wells” and the “irrigation” curves, signifying the dominant influence of irrigation withdrawal on stream depletion. Comparatively, the impact of non-irrigation pumping is minimal.

4.7 Summary and Conclusions

Alluvial aquifers in semi-arid environments support a variety of human activities because they frequently are productive, dependable, and easily exploited. These aquifers also are critical to aquatic and wetland ecosystems because they recharge overlying streams during non-flood periods. Consequently, overexploitation or improper management jeopardizes the viability of surface streams that depend on them. In this study, Visual MODFLOW, a numerical simulation model was used to investigate the impacts of groundwater pumping on stream-aquifer interactions in the A&T aquifer in northwestern Oklahoma. The results confirm that non-flood flow in the Beaver-North Canadian River network depends heavily on baseflow contributions from the alluvial aquifer. Before the onset of pumping baseflow contributed 56% to streamflow during the non-flood period, while 30% of stream leakage recharged the aquifer. With pumping, baseflow contribution decreased to 47%, 35%, and 27% after, respectively, 1, 5, and 15 years of pumping. Conversely, stream leakage increased to 35%, 44%, and 48% respectively, for the same pumping durations.

An important contribution of this study is that it disaggregates the basin-wide stream-aquifer dynamics by segments. The results show that the study area as a whole could be considered a gaining system but one segment is predominantly losing.

In general, whether a given stream reach gains or leaks water depends on complex interactions among anthropogenic, hydrogeologic, and climatic factors. The relative significance of these factors was not investigated explicitly. However, our preliminary findings appear to indicate that well density, proximity to stream channel, and magnitudes of water withdrawal are important anthropogenic variables. This is reasonable intuitively but more research is needed to quantify the effects of individual variables.

In terms of water use by activity or sector, irrigation demand is by far the most important process, accounting for up to 93% of total stream depletion after 15years of pumping.

Overall therefore, the study provides a framework for isolating and quantifying the impacts of water withdrawal on streamflow depletion both spatially and in terms of water use sectors. This is an important first step but more remains to be done to improve sustainable water use and management in the world's arid and semi-arid regions.

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Chapter 5

Alluvial Aquifer Response to Climate Variability and Groundwater Exploitation on the United States Southern Great Plains

ALLUVIAL AQUIFER RESPONSE TO CLIMATE VARIABILITY AND GROUNDWATER EXPLOITATION ON THE UNITED STATES SOUTHERN GREAT PLAINS

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Abstract

A numerical groundwater flow model of the alluvium and terrace aquifer (A&T aquifer) along the Beaver-North Canadian River (BNCR) in northwestern Oklahoma was implemented in Visual MODFLOW and used to evaluate the aquifer's response to scenarios of climate variability and anthropogenic groundwater pumping. Decadal water demand for northwestern Oklahoma is projected to increase 53% by the year 2050. Meanwhile, projections for regional precipitation indicate possible drier conditions in future decades, creating a problem of demand and supply. MODFLOW's predictive capabilities were utilized to evaluate the possible impacts of (1) the OWRB-projected regional water demand, (2) a severe drought, (3) a moderate drought, (4) a wet period, and (5) a human adjustment scenario, on the A&T aquifer. Results indicate that the combined impacts of anthropogenic pumping and droughts would create aquifer drawdowns of greater than 12 m. Spatially however, areas of high drawdown will be localized around areas having large well clusters and or zones of high intensity pumping. The worst impacts of both pumping and droughts will be on stream-aquifer interactions. For example, the OWRB-projected pumping would reduce baseflow by 27% (by 2050), increase stream leakage by 13%, and cause the BNCR to become a losing system beyond the year 2010. Similarly, the severe drought would lead to a 59% decrease in baseflow. Simulation results for the human adjustment scenario indicate aquifer drawdown will be reduced by 12%, while stream depletion will be reduced by 20%. By simulating various stress scenarios on the alluvial aquifer, this study provides information necessary for evaluating a number of management options for the aquifer.

Key words: Numerical simulation, northwestern Oklahoma, MODFLOW, alluvial aquifer, climate variability.

5.1 Introduction

Semi-arid northwestern Oklahoma on the southern Great Plains of the United States is facing a dilemma. On the one hand, Global Circulation Models (GCMs) indicate the region is likely to experience precipitation decreases of up to 25% due to climate variability and change (USGCRP, 2000). On the other hand, water demand is projected to increase 53% by 2050 (OWRB, 1997), creating a yawning gap between supply and demand. The combined impacts of these dynamics have been investigated extensively for bedrock aquifers (e.g. Chen et al. 2001; Eckhardt and Ulbrich 2003; Loáiciga et al. 2000; Rosenberg et al. 1999; Brouyère et al. 2004; Holman 2006). Chen et al. (2001) for example, investigated the possible impacts of climate change on regional water demand and supply as well as on the economy of San Antonio, Texas, which is dependent on the Edwards aquifer. They found that climate change would reduce aquifer yields but increase water demand such that a regional welfare loss of \$2.2-\$6.8 million per year may occur. In Belgium, Brouyè et al. (2004) showed that climate change would decrease groundwater recharge, water levels, and thus storage, in a chalky aquifer. In contrast, few studies have examined the impacts of climate change and anthropogenic water use on alluvial aquifers (e.g. Chen and Chen 2004; Don et al. 2006; Alemayehu et al. 2007; Rejani et al. 2006). Alemayehu et al (2007) found that anthropogenic overexploitation of an alluvial aquifer has dried up two important lakes in eastern Ethiopia due to reduced baseflow to the lakes. Similarly, Rejani et al (2007) utilized a 3-D groundwater model to investigate impacts of groundwater exploitation on the Balasore coastal alluvial basin in India. The study found that aquifer overexploitation has caused several shallow tube wells to go dry as groundwater levels have declined by more than 4 m. Additionally, they report the intrusion of sea water into the aquifer. For northwestern Oklahoma, Davis and Christenson (1981) investigated the impacts of aquifer pumping on groundwater levels using a 2-dimensional numerical groundwater model. The study projected that stressing the aquifer from 1978 to 2020 at the 1977 pumping rates would have little effect on the aquifer, decreasing its saturated thickness only by an average of 0.5 m. The study however, did not consider impacts of climate variability on the aquifer.

The importance of alluvial aquifers in arid and semiarid world regions is well documented (e.g. Cui and Shao, 2005; Bronstert et al, 2000; Döll and Hauschild, 2004; Workman and Serrano, 1999). They sustain flow in regional streams during dry periods and are critical therefore for maintaining riparian ecosystems. Additionally, alluvial aquifers support domestic, municipal, and agricultural water supplies. For example, on the African Sahel savanna where water supplies are still largely dependent on unregulated natural sources, settlements often are clustered within alluvial basins because their shallow groundwater systems provide remarkable defense against the region's persistent droughts (Cater and Alkali, 1996; Tarhule and Woo, 1997; 2002). On the Southern Great Plains of the United States, studies have shown that some alluvial aquifers have higher yields than adjacent bedrock aquifers (Ryder, 1996). As a result, alluvial aquifers are exploited extensively for irrigation, and have contributed to making the Southern Plains one of the most agriculturally productive regions of the United States. Yet, the region is prone to episodic droughts with attendant water shortages (Covich et al., 1997; Zume and Tarhule, 2006). If future water demand increases and droughts intensify or become more persistent, the regions agricultural and economic base could be compromised. Such consideration suggests a need to investigate various scenarios of precipitation variability and water demand as a basis for water resources planning and management, not only for the southern plains, but other semi-arid regions of the world facing similar challenges. This study is a contribution towards that goal. It simulates the response to climate variability and anthropogenic water withdrawals of the alluvium and terrace aquifer (A&T for brevity) of the Beaver-North Canadian River in Northwestern Oklahoma. The simulation approach attempts to replicate real-word complexity by integrating components of the physical hydrogeologic system, climatic, and anthropogenic stresses, thereby providing multifaceted insights about system dynamics, including future outlooks (e.g. Senthulkumar and Elango, 2004; Abderrahman and Rasheeduddin 1994; Kirshen 2002; and Rainwater et al. 2005). Thus, by simulating several scenarios, insights can be obtained that provide for water resources managers, the means to evaluate and reconcile competing management alternatives.

5.2 The Study Area

5.2.1 LOCATION, PHYSIOGRAPHY, AND CLIMATE

The A&T aquifer is the most important regional source of fresh water in northwestern Oklahoma, supplying water for irrigation, municipal, stock, and industrial uses (Adams et al., 1997). Covering 2150 km^2, the aquifer is located within the Western Sand-Dune belt geomorphic province of northwestern Oklahoma (Fig. 1; Johnson et al., 1972). The land surface elevation decreases from about 701 m above mean sea level (m.a.m.s.l) in the northwestern part to about 488 m in the southeast (Davis and Christenson, 1981). Local relief however, is generally less than 30 m. The regional climatic setting is semi-arid with mean annual precipitation of approximately 664 mm. More than 80% of precipitation

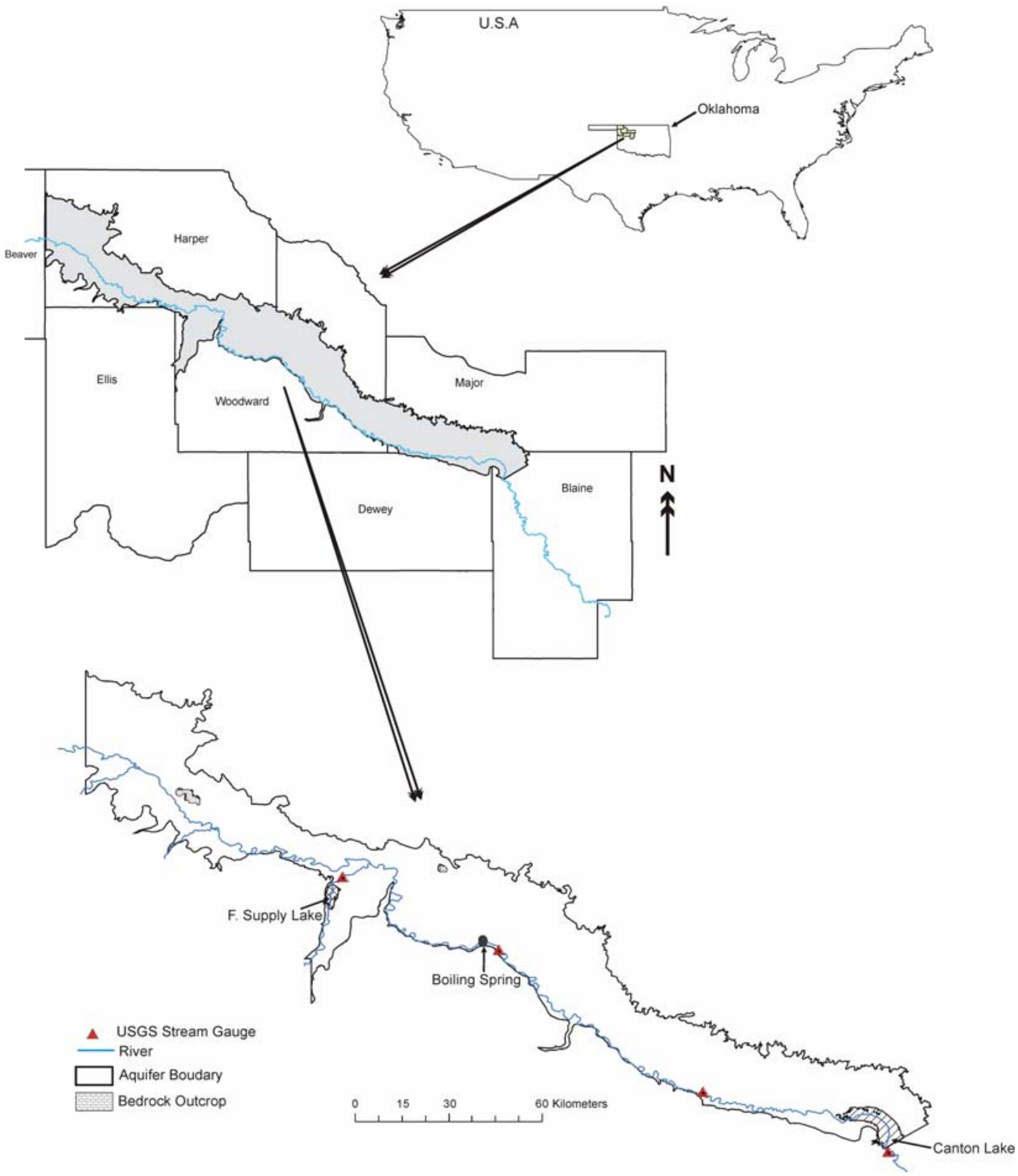

Figure 1: Location of the study area

falls between March and October with May and June accounting for 16 and 13% respectively of total precipitation (16% and 13% respectively). In common with most semi-arid environments, year-to-year precipitation variability is high with a coefficient of variability of about 19%. Temperatures average about 15.6^0 C, with a slight increase from

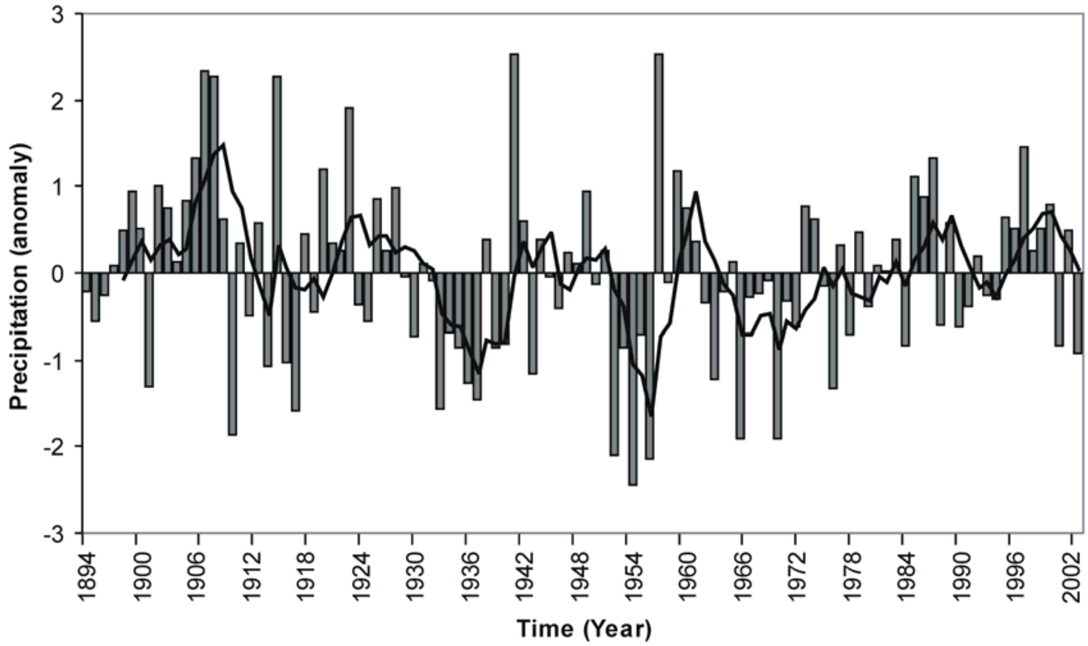

Figure 2: Standardized precipitation (anomaly) plot for northwestern Oklahoma (1894-2003). Thick line is the 5-year running mean.

north to south. Wind direction varies slightly from north to south as well. Whereas most of the northern one third experiences south-southwesterly winds, south-southeasterly winds dominate in the southern part. These wind systems appear to have some implications for the geomorphology of the study area.

Northwestern Oklahoma, like many other locations in the Southern Plains, is drought-prone, evident from the region's standardized precipitation index shown in Figure 2. The worst drought in recent history occurred between 1953 and 56 (PDSI >-3). Serious water shortages accompanying these droughts (OWRB, 1997) portend severe adverse implications for social and agroeconomic activities. The surface drainage network is sparse and still characterized by high evaporative losses, ranging from 1422 to 1626 mm, on average, about 230% of regional annual precipitation (OWRB, 1997). The high evaporative demand on surface sources also, has created surface water quality issues. Yet, the region supports some of the most extensively irrigated farmlands in the State of Oklahoma (OWRB, 1997). The combined effects of sparse surface sources, unreliable streamflows, and poor surface water quality, have elicited a heavy dependence on the A&T aquifer.

5.2.2 HYDROGEOLOGY

The A&T aquifer is composed primarily of Quaternary deposits, which occur mainly north of the Beaver-North Canadian River (Davis and Christenson, 1981). These deposits are oriented concordantly relative to the river, the result of the river's southerly migration down the regional dip of the underlying red beds and the influence of dominant southerly winds. The Quaternary deposits consist of four geologic units: the high and low terrace deposits, the alluvium, and the dune sands. The thicknesses of these deposits vary spatially. The high terrace deposits, which occur farthest from the present river channel, vary in thickness from 0 to 91 m, with an average of about 21 m. These deposits are of Pleistocene age, and are believed to have been derived by the reworking of the Ogallala and the adjacent Permian formations (Davis and Christenson, 1981). The low terrace deposits average about 15 m in thickness. The main river channel and its floodplain are made up largely of alluvial deposits of Holocene age and have an average thickness of about 9 m. Overlying most of the study area are dune sands, which are derived from the underlying terrace and alluvium deposits. The dune sands are unsaturated usually but greatly facilitate recharge to the alluvial aquifer. The terrace and alluvium deposits are the principal water-bearing units. They comprise of poorly sorted, fine to coarse-grained, unconsolidated quartz sand, containing minor amounts of clay, silt, and basal gravel (Davis and Christenson, 1981). There is some evidence that the alluvium and terrace deposits are hydraulically connected and constitute a single aquifer unit that is generally unconfined. Information from drillers' logs supplied by the Oklahoma Water Resources Board suggests the base of the aquifer at most locations is the top of the Permian red beds Formation. The red beds are relatively impermeable and act as a barrier to vertical water leakage from the aquifer. Depth to bedrock varies spatially with a maximum of about 100 m. At a few locations however, the bedrock outcrops at the surface. The Tertiary Ogallala and the Rush springs Formations underlie the aquifer in the northwestern corner.

The Beaver and the North Canadian Rivers, together with their tributaries are the major rivers in the study area. The Beaver River enters Oklahoma from New Mexico. It flows, first easterly, then southeasterly, becoming the headwaters of the North Canadian River at its confluence with Wolf Creek (see Figure 1). Known as the North Canadian From this point downstream, the river continues its southeasterly flow across central Oklahoma before joining the Canadian River to empty into the Arkansas. Davis and Christenson (1981), coined the term "Beaver-North Canadian River" to refer to the combined river channels of the Beaver and the North Canadian Rivers. Joining the Beaver-North Canadian River from the south are a few seasonal tributary streams that drain the southern areas underlain by Permian and Tertiary formations.

Two storage reservoirs are located within the area. Fort Supply Lake is located on Wolf Creek in Woodward County. Further downstream on the North Canadian River, Lake Canton is located near the city of Canton in Blain County.

5.3 Numerical Simulation

5.3.1 MODEL CONCEPTUALIZATION AND DEVELOPMENT

A three dimensional groundwater flow model with variable spatial resolution was implemented using Visual MODFLOW (VM). VM (4.1), a proprietary product of Waterloo Hydrogeologic Inc. (2005), has enhanced capabilities for pre- and post-processing input and output data for the well- established U.S. Geological Survey (USGS) groundwater flow code, MODFLOW (McDonald and Harbaugh 1988). MODFLOW has been applied extensively for investigating impacts of groundwater pumping or climate change on groundwater dynamics (e.g. Croley and Luukkonen, 2003; Kirshen, 2002; 2004; Varni and Usunoff 1999; Wilsnack et al. 2001).

The A & T aquifer was discretized into a finite-difference grid of 43,384 cells, comprising 187 rows and 232 columns oriented in the direction of regional groundwater flow. Cell sizes were set at 0.35 km per side, except for cells containing pumping wells, which were further refined to center the wells at their nodes. Vertically, the aquifer was discretized into three layers to enhance its ability to calculate heads in the vertical direction. The discretization was done with consideration of the hydrogeologic framework described earlier. Aquifer top elevations were derived from a digital elevation model (DEM), while layer elevations were determined from well-completion reports and logs contained in the Oklahoma Water Resources Board's ORACLE database (www.owrb.state.ok.us/wd/search/search.php).

5.3.2 BOUNDARY CONDITIONS

The aquifer was bounded by no-flow boundaries at groundwater divides. Also, the aquifer base was treated as a no-flow boundary, consistent with the regional bedrock geology. Two reservoirs, Fort supply and Canton Lakes, located within the model domain, were represented by constant head cells. The Tulsa district of the U.S. Army Corps of Engineers (www.swt-wc.usace.army.mil) provided the stage data for the lakes. Subsurface inflow to the aquifer from the upstream end, and outflow at the downstream end, were simulated with general head boundaries. Alluvial deposits extend beyond the geographic limits of the study area at both ends. Consequently, drain cells were used to simulate leakage from the aquifer to the adjacent Cimarron alluvium on the northeastern corner of the study area. Similarly, aquifer discharge through the main spring at Boiling Springs Park was simulated with drain cells. Spring discharge obtained from the Park's office was 164 m^3/day. In both cases, drain conductances were first assigned arbitrarily and then modified during model calibration. Subsurface inflow to the aquifer from the Ogallala formation around the southwestern part of Harper County was represented by constant flux nodes using the recharge package. Figure 3 shows the finite-difference grid and the boundary conditions used.

Direct precipitation recharge to the aquifer was assumed to be 10% of annual precipitation. Thus, consistent with the range in annual precipitation, the recharge varied from 6.96×10^{-5} m/day in the western part of the aquifer to 1.39×10^{-4} m/d in the southern part, with an average of 1.03×10^{-4} m/d. Irrigation return flow was assumed to be 20% of annual irrigation pumpage (e.g. Davis and Christenson, 1981). This amount was not added explicitly as recharge in the model. Instead, reported withdrawal at each irrigation well was reduced by 20% to account for the return flow. This approach avoids assigning higher recharge values to areas without irrigation wells. Evapotranspiration (E_P) was not simulated in the model because the area contributing E_p is less than 1% of

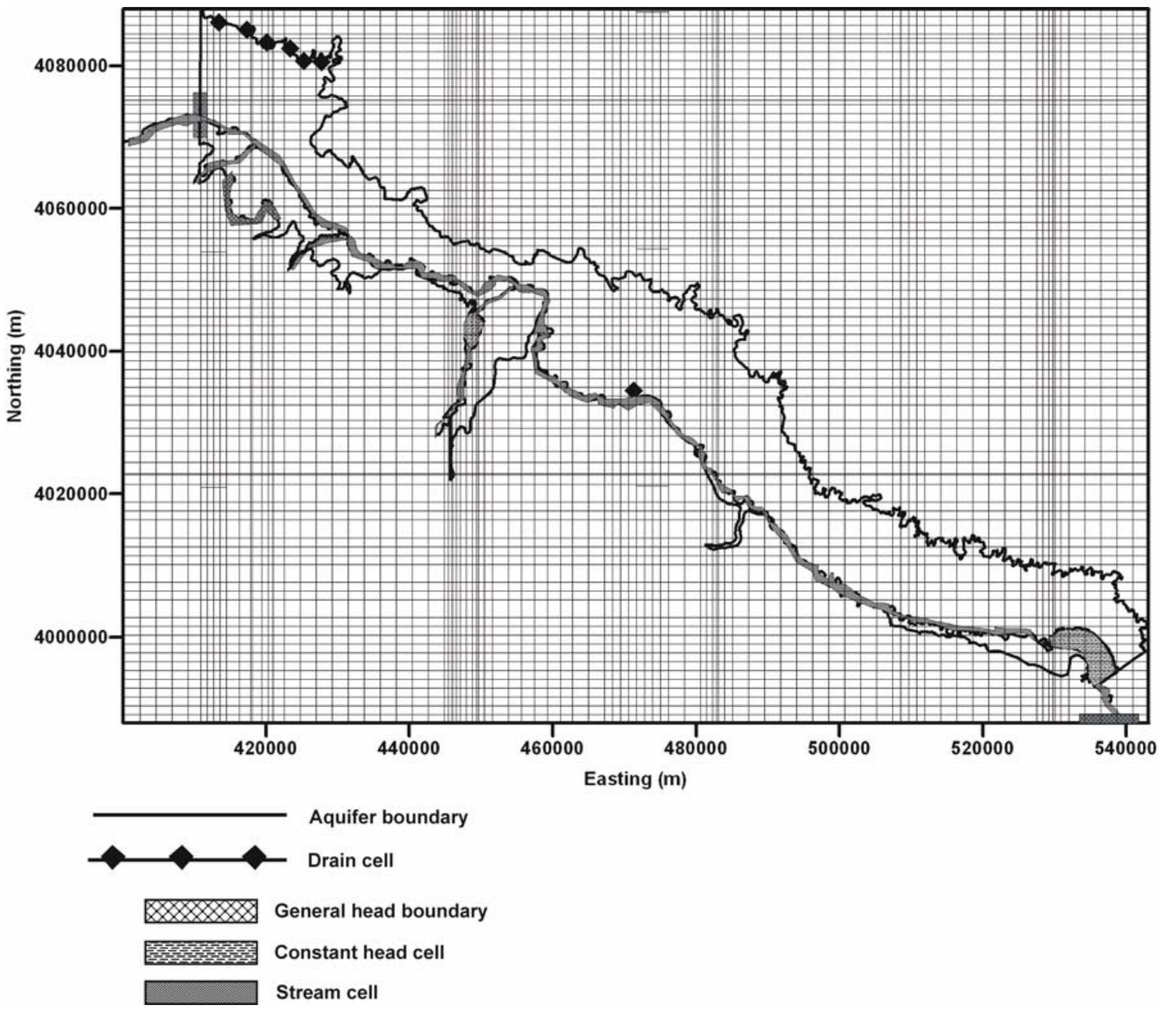

Figure 3: Finite difference grid showing model boundary conditions

the model domain. Groundwater withdrawal (an internal boundary) was specified in the model at 131 nodes representing actual locations of pumping wells. Annual pumping rates at each well were based on water use reports submitted annually to the Oklahoma water resources Board by permit holders.

Stream-aquifer interactions were simulated with the streamflow routing package developed for MODFLOW by Prudic (1989). Conceptually similar to the river package in MODFLOW, the streamflow routing package has the additional capability to track the amount of water in each simulated stream segment. Stream stage was computed iteratively using Manning's roughness coefficient. This approach is superior to that used in the river package where river stage must be kept constant for each stress period. Simulations were performed for both steady and non-steady state conditions. The BNCR and its tributaries were simulated as head-dependent flux boundaries. All rivers were simulated as partially penetrating with leaky riverbeds. Along a river segment, each model cell constitutes a river reach; hence, the entire river system consisted of 502 reaches. Digital data for different river segment, including average flows and channel characteristics (e.g. stage, slope, width, and Manning's roughness coefficient) were obtained from the US EPA's BASINS program (version 3.1). The BASINS program is a multi-purpose environmental analysis system that integrates a geographic information science (GIS), national watershed data, and other environmental assessment and modeling tools into a single package. The program is available for free download at www.epa.gov/waterscience/basins. Within the BASINS program is the Reach File (RF1) package containing a database of approximately 1,126,300 km of streams with related hydrologic data for the conterminous United States. The RF1 package was queried for specific data on the BNCR watershed. Additionally, stream discharge data was available at four USGS gauging sites (www.waterdata.usgs.gov/ok/nwis) located in the study area.

5.4 Model calibration

The groundwater model was calibrated to both quasi-steady-state (QSS) and transient conditions. This dual calibration matches observed and stimulated conditions at multiple time steps thereby reducing uncertainty in parameter estimates (e.g. Allen et al. 2004; Brouyère et al. 2004). Calibration to QSS conditions was achieved using the automatic Parameter Estimation program, PEST (Doherty 2001). PEST automatically adjusts model parameters until the fit between model outputs and observations is optimized. The process calculates also the sensitivity of each parameter to model results.

The QSS calibration matched calculated hydraulic heads and average groundwater level elevations in observation wells. Simulated baseflows also were matched with average baseflows separated from observed streamflow records at four USGS streamflow gauging sites in the study area. In general, the Oklahoma Water Resources Board makes groundwater level measurements during the winter months (December-March) when anthropogenic impacts are minimal. Therefore, the average groundwater levels measured during the winter months (1978-79) were used as targets for the QSS calibration.

The parameters modified during the calibration process include hydraulic conductivity (K), Streambed and drain conductances, Manning's roughness coefficient (*n*), and recharge. Initial distribution of K was based on a previous report (Davis and Christenson, 1981) and an initial *n* value of 0.05 was assigned to all stream segments. Streambed and drain conductances were assumed because no prior information existed for them. The K distribution was adjusted until the observed and simulated hydraulic heads were matched. However, in order to ensure robustness of calibrated results, it is necessary to match also, calculated and measured fluxes. Thus, after matching the heads, recharge, streambed conductances, and *n* were adjusted until calculated and measured streamflows and baseflows also matched satisfactorily.

Transient model calibration was achieved by trial-and-error. The transient simulation spanned a 15-year period (1979-1994). The result of the QSS calibration provided initial conditions for the transient simulation. Groundwater pumping was introduced over a single stress period, divided into 30 time steps with a minimum time step of 4.6 days and a maximum of 5475 days (15 years). The pumping rate at each pumping well was the average of actual withdrawal reported over the 1979-94 period. These vary from 73 to 6393 m^3/d. Calibration was achieved by adjusting the specific yield (S_y) until simulated heads matched annually observed groundwater levels in observation wells. The process necessitated a slight adjustment of the previously adjusted parameters (K, n, streambed conductances, and recharge) during the QSS calibration in order to match also simulated and observed fluxes.

5.5 Predictive Scenarios

Three sets of predictive model runs were performed to evaluate the response of the A&T aquifer to impacts of different stress scenarios. These are as follows: (1) the water demand scenario, which assesses the response of the aquifer to regional anthropogenic water demand as projected by the OWRB; (2) climate variability scenarios, simulated to evaluate the impacts of climate variability specifically, recharge, on the alluvial aquifer; and (3) an adaptive scenario, simulated to assess the possible impacts of improved water management strategies on the A&T aquifer.

Using the amount of water demand in 1990 as base, the OWRB predicts water demand in northwestern Oklahoma will be approximately 53% higher by the year 2050 (OWRB, 1997). Figure 4 shows the projected percent demand increase for each decade.

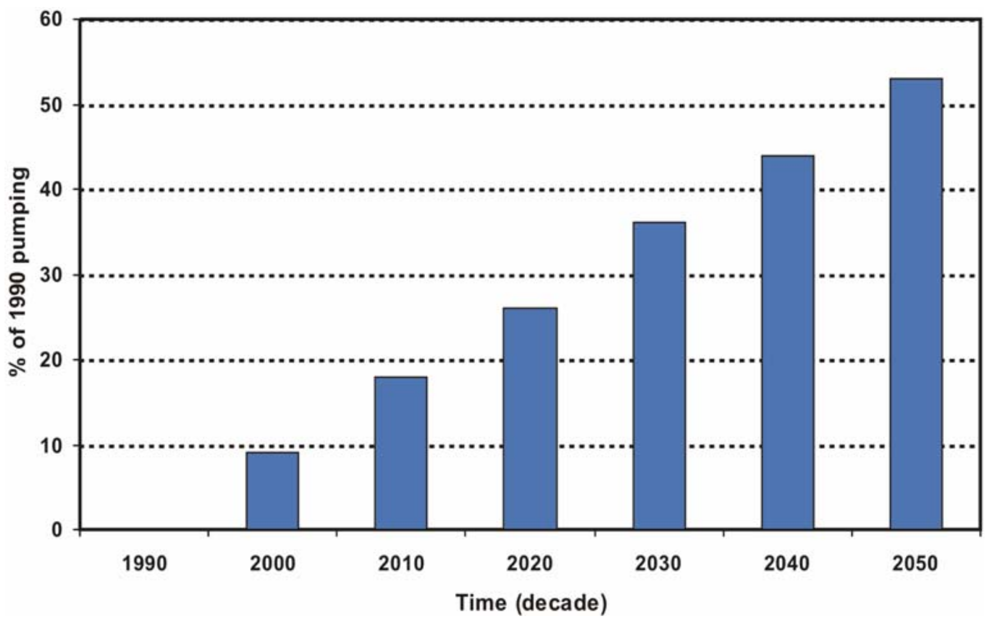

Figure 4: Projected aquifer pumping for the demand scenario.

Note however that the above projection is not exclusively for groundwater; nonetheless, because groundwater from the A&T aquifer is the principal source of regional water demand, this study treats the projected demand as demand on the aquifer. Thus, for purposes of this study, the reported 1990 groundwater withdrawal from the A&T aquifer is increased according to the OWRB-projected percentages. In the model, the demand scenario is represented in a 60-yr model run (1990-2050) divided into six stress periods, each a decade long. During the simulation, model-calibrated recharge was held constant, while groundwater withdrawal for each stress period was varied according to the projected water demand for the corresponding decade. Total annual withdrawal under this scenario varied from 131,828 m^3/d in 1990 to 201697 m^3/d in 2050.

The study investigated three climate variability scenarios, including a moderate drought, a severe drought and a wet period. These conditions are assumed to manifest largely as deviations from the normal amounts of groundwater recharge. For purposes of this study, a climatic scenario is defined by an assumed percentage of the model-calibrated (normal) recharge. This conservative approach of assuming recharge inputs for climatic scenarios is routinely used in climate-groundwater impacts assessment studies (e.g. Rainwater et al. 2005). Specific recharge scenarios used to assess climatic impacts were increases or decreases in the normal recharge by 25%, 30%, or 50% depending on the specific event. Simulation of these scenarios, in tandem with accompanying anthropogenic groundwater withdrawal scenarios, provided insight about the potential effects of climatic variability and anthropogenic stresses on the A&T aquifer.

The first climatic scenario simulated was a "severe drought", spanning a 4-year period, consistent with the worst drought (in terms of duration; 1953-56) on recent historical precipitation record (1894-2003) for the study area (refer to Figure 2). This period also has the highest cumulative precipitation deficit on the record. In the model, the severe drought was represented as a 4-yr stress period during which the calibrated aquifer recharge was assumed to be reduced by half. Note that this assumption is arbitrary because there is no sure way of relating historical precipitation deficits to recharge. It was also assumed that such prolonged dry conditions would lead to a doubling of normal aquifer pumping; hence, the pumping rate at each withdrawal well was doubled for the stress period. Normal pumping here refers to the average aquifer withdrawal for the 2000-2004 period, which was the base pumpage used for projecting impacts of all climatic scenarios. This scenario was performed to assess the response of the A&T aquifer, should a severe drought, comparable in duration to the 1953-56 droughts, occur in the future in northwestern Oklahoma.

Next, a moderate (2-yr) drought was simulated, again, represented in the model over a 2-yr stress period, with impacts assumed to be half those of the severe drought. Droughts of this duration are common features of northwestern Oklahoma climate (see Figure 2; Zume and Tarhule, 2006). Specifically, the moderate drought, it was assumed, would reduce the normal aquifer recharge by 25% and cause a 50% increase in aquifer withdrawal at each pumping well.

The final climatic scenario was the simulation of a wet period, executed to assess the response of the A&T aquifer to a potentially wetter climate. From the historical precipitation record in Figure 2, the longest wet period occurred between 1902 and 1909. This duration was simulated in the model, represented by a stress period, 8 years long. The wet conditions were simulated assuming a 30% increase in the normal aquifer recharge. Similarly, it was assumed that pumping at each well during this wet period will be reduced by 50%.

Finally, a scenario accounting for future human adjustments in water use habits, including the use of more efficient irrigation technologies, was simulated. For this scenario, recharge was left unaltered at the normal. However, it was assumed such adjustments will reduce groundwater pumping by 25%. Results of these simulations are discussed in the next section.

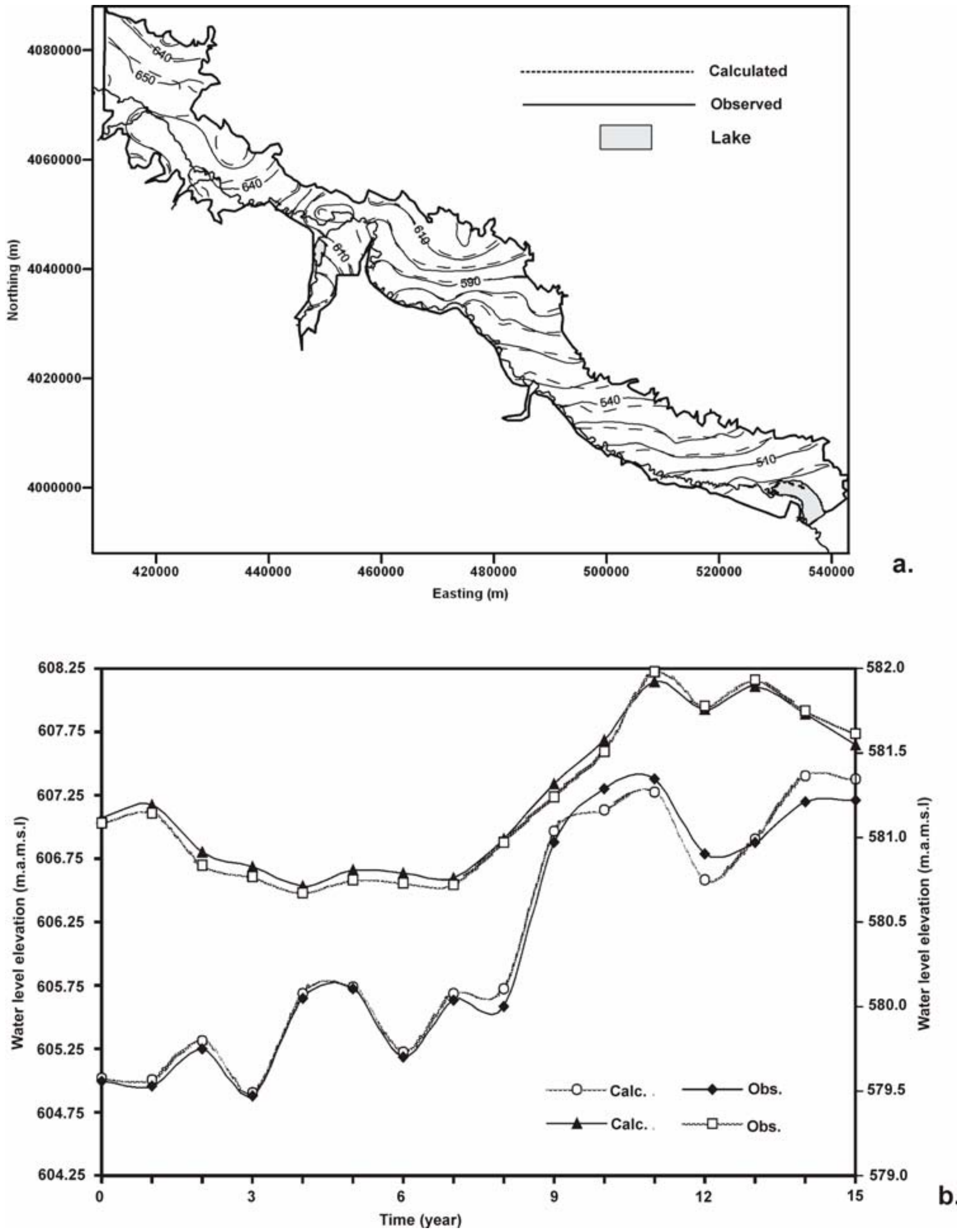

Figure 5: (a) QSS calculated vs. observed head contours, (b) calculated vs. observed groundwater elevation at two observation wells (transient).

5.6 Results and Discussions

5.6.1 CALIBRATION

Figure 5a uses isopleths to illustrate the strong agreement achieved between simulated and observed hydraulic heads for the quasi steady-state (QSS) calibration. Analysis of the degree of agreement at individual well points indicate that , 29% of 91 observation points, had residuals between 0 and ±1.5 m, 47% between ±1.5 and 2.5 m, and 20% between ±2.5 and 3.5 m. Only 4% had residuals greater than 3.5 m. To put these deviations in proper perspective, it is helpful to consider that in terms of depth to actual water table they represent errors of about 10 – 15% for the range of well depths included in this study. The mean of the absolute residual (MAR) was 2.34 m, well within the error range of the digital elevation model (DEM) used to derive water level elevations, and errors in the water level measurement themselves. The agreement between simulated and observed groundwater levels for the transient calibration is shown in Figure 5b for two representative observation wells.

Calibrated hydraulic conductivity (K) values for the aquifer range from 0.78 to 65 m/d, with an average of 30.81 m/d. The value of K at the low end is consistent with that reported by Davis and Christenson (1981) for the aquifer, but the upper limit is significantly higher than their results (49 m/d). It is possible that differences in study well locations and configuration as well as the local geologic conditions around well clusters used in the two studies may account for this disparity. Indeed, Wood and Stacey (1965) reported K values of up to 61 m/d from six pumping tests within the aquifer, which is reasonably close to the upper value of K obtained in this study. The specific yield ($S_{y)}$ obtained for the aquifer is 0.28. This compares favorably with the value of 0.29 reported by Davis and Christenson (1981). Model-derived streambed conductances range from 63 to 6038 m^2/d for different reaches of the Beaver-North Canadian River.

The simulated pre-development potentiometric surface (Figure 5a) indicates groundwater level slopes in a northwest-southeast direction consistent with basin

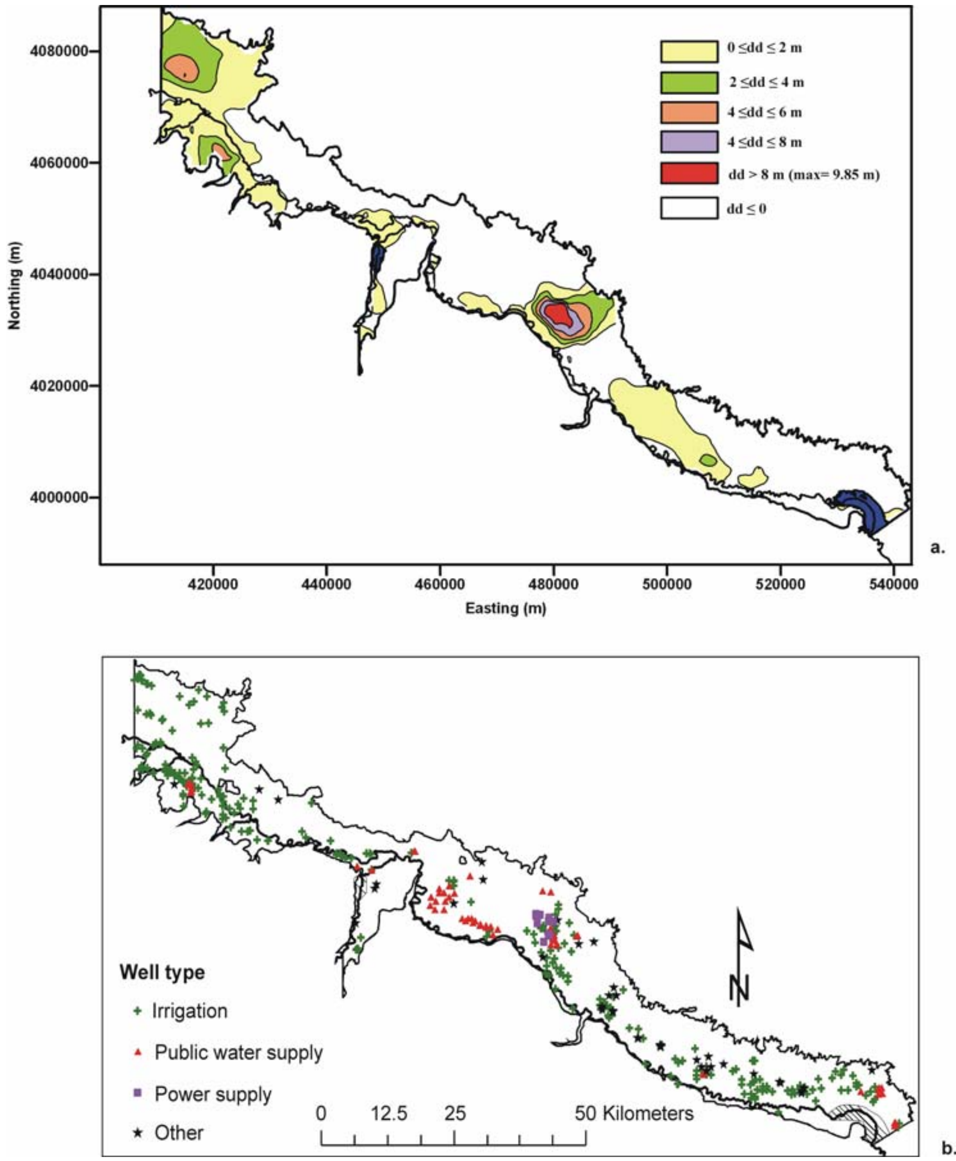

Figure 6: (a) Projected drawdown at the end of year 2050 (demand scenario), (b) Map showing the distribution of pumping wells within the aquifer.

topography; however, flow is generally southwesterly towards the Beaver-North Canadian River. On the northern end of the aquifer, around the NW part of Harper County (refer to Figure 1), potentiometric contours indicate groundwater discharges from the aquifer adjacent basins. Similarly, potentiometric contours suggest groundwater seeps into the aquifer from the adjacent Ogallala formation in southwestern Harper County, near its border with Beaver County. Both seepages were represented with head-dependent boundaries as discussed in section 3.2 (Figure 3). Mass balance for the calibrated model shows that direct precipitation recharge is the major input to the aquifer (66%), followed by stream leakage, which accounts for 30% of aquifer recharge. Groundwater seepage from the adjacent Ogallala formation and upper end alluvium constitutes 3% of total inflow, while seepage from the Fort supply Lake accounts for roughly 1%. On the output side, groundwater discharge to streams (baseflow) is the largest source of outflow from the aquifer (56%). Groundwater also exits the aquifer into lakes (32%), adjacent groundwater basins (11%), and as spring flow (<1%). These results are consistent with those reported by Davis and Christenson (1981) for this aquifer, and those for similar aquifers in western Oklahoma (e.g. Adams et al. 1996). The above results suggest that both natural climatic variability that alters the amount and timing of precipitation, and anthropogenic groundwater pumping, can be expected to have significant influence on aquifer recharge, and similarly, baseflow contribution to streams.

Table 1: Decadal changes in drawdown and aquifer saturated thickness under the demand scenario

Year	2000	2010	2020	2030	2040	2050
Drawdown (m)						
Average.	0.73	1.06	1.55	1.60	1.81	1.95
Maximum.	6.59	7.51	7.94	8.46	9.18	9.85
Saturated Thickness (m)						
Average.	14.16	14.11	14.00	13.94	13.93	13.91
Maximum.	33.69	33.07	32.46	32.20	32.13	32.07

5.6.2 PREDICTIVE SIMULATIONS

The impacts of the predictive model runs (the demand and the climatic scenarios) on the A&T aquifer are evaluated in terms of drawdowns (or the changes in hydraulic head between two time periods), aquifer saturated thickness, and stream-aquifer interactions. While each of these parameters is an indicator of stress-impact on the aquifer, the use of all three provides a more complete picture of the range of impacts possible for a given stress or combination of stresses. Detailed results are presented below.

5.6.2a EFFECTS OF THE DEMAND SCENARIO

Table 1 shows changes in average drawdown and aquifer saturated thickness from 2000 to 2050, under the demand scenario pumping. These changes are with reference to the 1990 conditions. It was observed that pumping under the projected demand scenario would lower groundwater levels unevenly across the A& T aquifer. For example, drawdown at the end of 2000 would range from 0 - 6.59 m, with an average of 0.73 m. As suggested by the low average value relative to the range of drawdown, only 26% of the aquifer areas experiencing water level decline have drawdown greater than 1 m. By the end of 2050 however, the average drawdown would increase to 1.95 m (165%). Although drawdown magnitudes will relatively be higher at the end of 2050, regionally, areas experiencing drawdown greater 2 m will still be localized. Notice in Table 1 that both average and maximum drawdown per decade increased linearly from one decade to the next, reflecting impacts of both longer pumping and increased withdrawal at subsequent higher decades. The rate of drawdown change per decade however, is non-linear, possibly due to the uneven number of model cells that go dry at different time

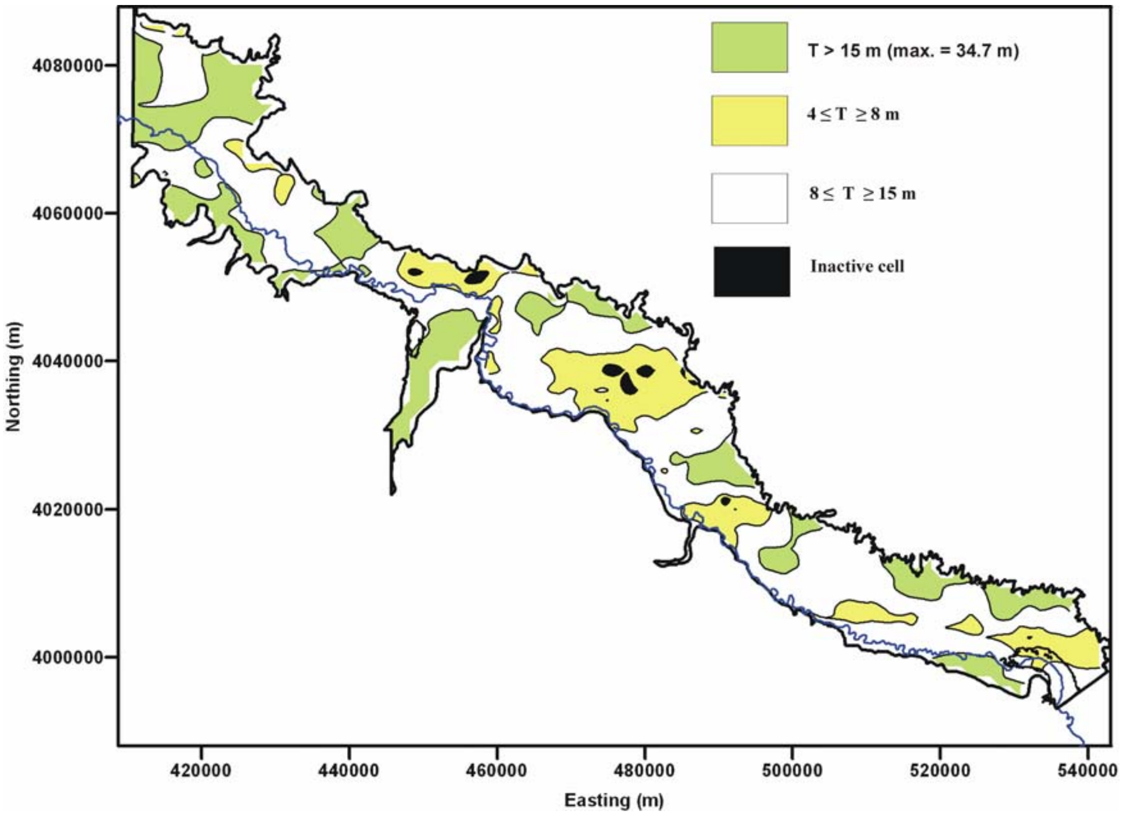

Figure 7: Projected aquifer saturated thickness at the end of 2050 (demand scenario).

steps when the pumped volume exceeds the amount of recharge in a model cell. It is also important to note that some areas of the aquifer, particularly those without pumping activity, will experience no drawdown or even a rise in the water table. Rising water levels in a model cell is designated as negative drawdown in MODFLOW. Figure 6a illustrates the spatial pattern of drawdown within the aquifer for the year 2050. This pattern is similar to the rest of the prior decades, the only difference being in the magnitudes of drawdown formed around areas of intensive pumping activity. Unshaded areas are those of zero drawdown or water table recovery. A comparison of Figure 6a with a map showing pumping well location (Figure 6b) suggests areas with significant drawdown are also those having large well clusters. Thus, the simulation results suggest impacts of the demand scenario on water levels will most likely be localized around areas of high pumping activity.

The projected decadal changes in aquifer saturated thickness (T_s) under the demand scenario are also shown in Table 1. At the end of each stress period, T_s was calculated for each model cell by subtracting the elevation of the aquifer base from the simulated hydraulic head. Hence, T_s in this work refers to the hydraulic head above the aquifer base. In computing changes in T_s from one stress period to the next, active model cells having $T_s < 1.5$ m were inactivated. This is because the State of Oklahoma defines an aquifer within its boundaries as a geologic unit having a saturated thickness of, at least, 1.5 m (Davis and Christenson, 1981). In general, the impacts of the demand scenario on T_s show patterns similar to those discussed above for drawdown. For example, T_s decreases also linearly with both intensity and duration of pumping. This is consistent with known and expected response to pumping of an unconfined aquifer because the water table elevation determines its saturated thickness. Thus, as the water level falls so does the saturated thickness. The difference in maximum T_s between 2000 and 2050 is 5.8% (1.62 m). This small change reflects the localized nature of drawdown created within the aquifer. The spatial signature of T_s at the end of 2050 under the demand scenario is shown in Figure 7.

Figure 8 shows the impact of aquifer pumping, under the demand scenario, on stream-aquifer interaction in the Beaver-North Canadian River (BNCR) basin. Pumping-induced impacts on streamflow manifest through baseflow reduction and enhanced stream leakage. As well pumping proceeds, cones of depression develop around the wells capturing groundwater that would otherwise end up in the stream as baseflow.

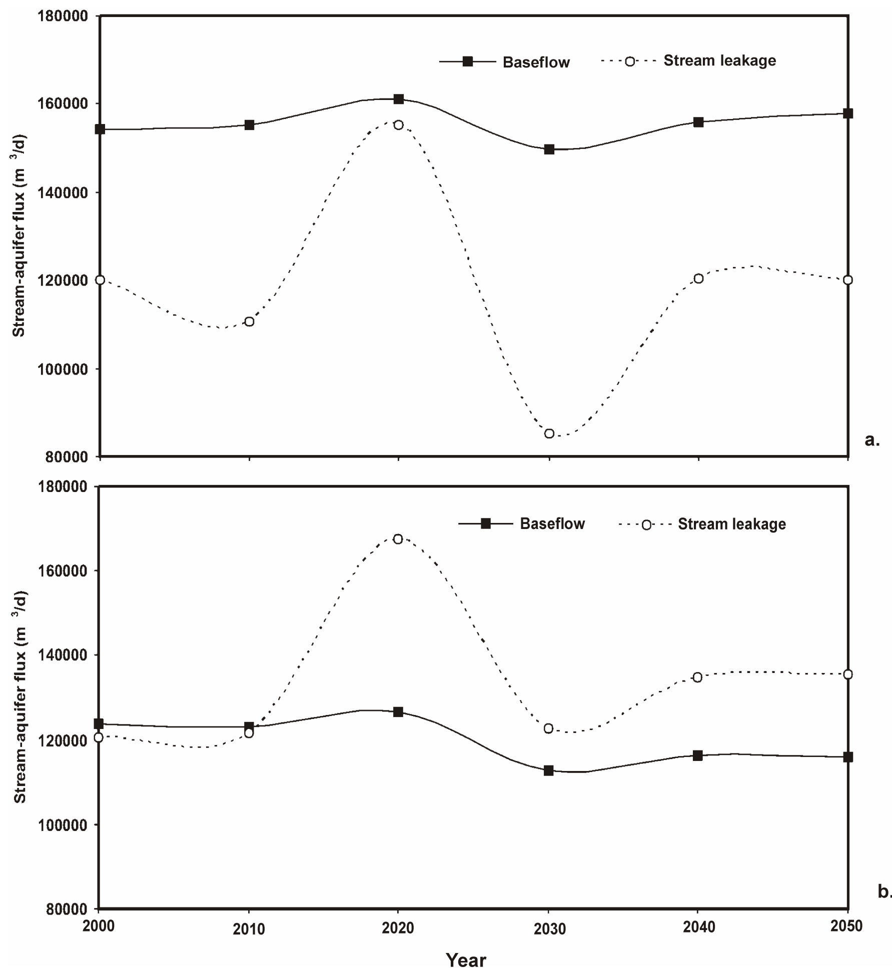

Figure 8: Stream-aquifer interaction (a) no pumping, (b) demand-scenario pumping.

Additionally, pumping-induced changes in hydraulic gradient stimulate direct stream leakage into the aquifer. Hence, the total stream depletion or loss is the combined losses due to intercepted baseflow and direct stream leakage. To isolate the impacts of pumping on stream-aquifer interaction, we first ran the transient model with no pumping introduced (Figure 8a). Then the model was run a second time with the demand scenario pumping (transient run; Figure 8b). In the first run (Fig. 8a) baseflow contribution to the stream is higher than stream leakage at all pumping times, signifying that the BNCR is a gaining system under non-pumping conditions. This result is consistent with that reported earlier for the QSS calibration. In contrast, the demand pumping scenario suggests baseflow will reduce by 27% while stream leakage will increase by 13%. As a result, the BNCR will become a losing system beyond the year 2010 (see the crossover point on Figure 8b).

5.6.3 CLIMATE VARIABILITY SCENARIOS

5.6.3a IMPACTS ON WATER LEVELS

Figure 9a, summarizes the potential impacts of the simulated climate variability scenarios on water levels (presented as drawdown) in the A&T aquifer. The shown current condition refers to a simulation of the actual 2000-2004 average pumping from the aquifer using the model-calibrated recharge. All impacts discussed are with reference to the current conditions. The simulated “severe drought” for example, would cause drawdown in the A&T aquifer in the range of 0 - 12.46 m, with an average of 2.03 m. In other words, assuming that pumping rates continue at the historical such severe drought would more than double drawdown in the aquifer relative to the current drawdown. To appreciate the possible impacts of such change, it is important to note that drawdown magnitudes on the order of even a few centimeters can have profound impact on basin ecosystems (Kirshen, 2002). However, only a few localized areas have drawdowns larger than 2 m. Figure 9b is a contour map of the drawdown caused by the severe drought

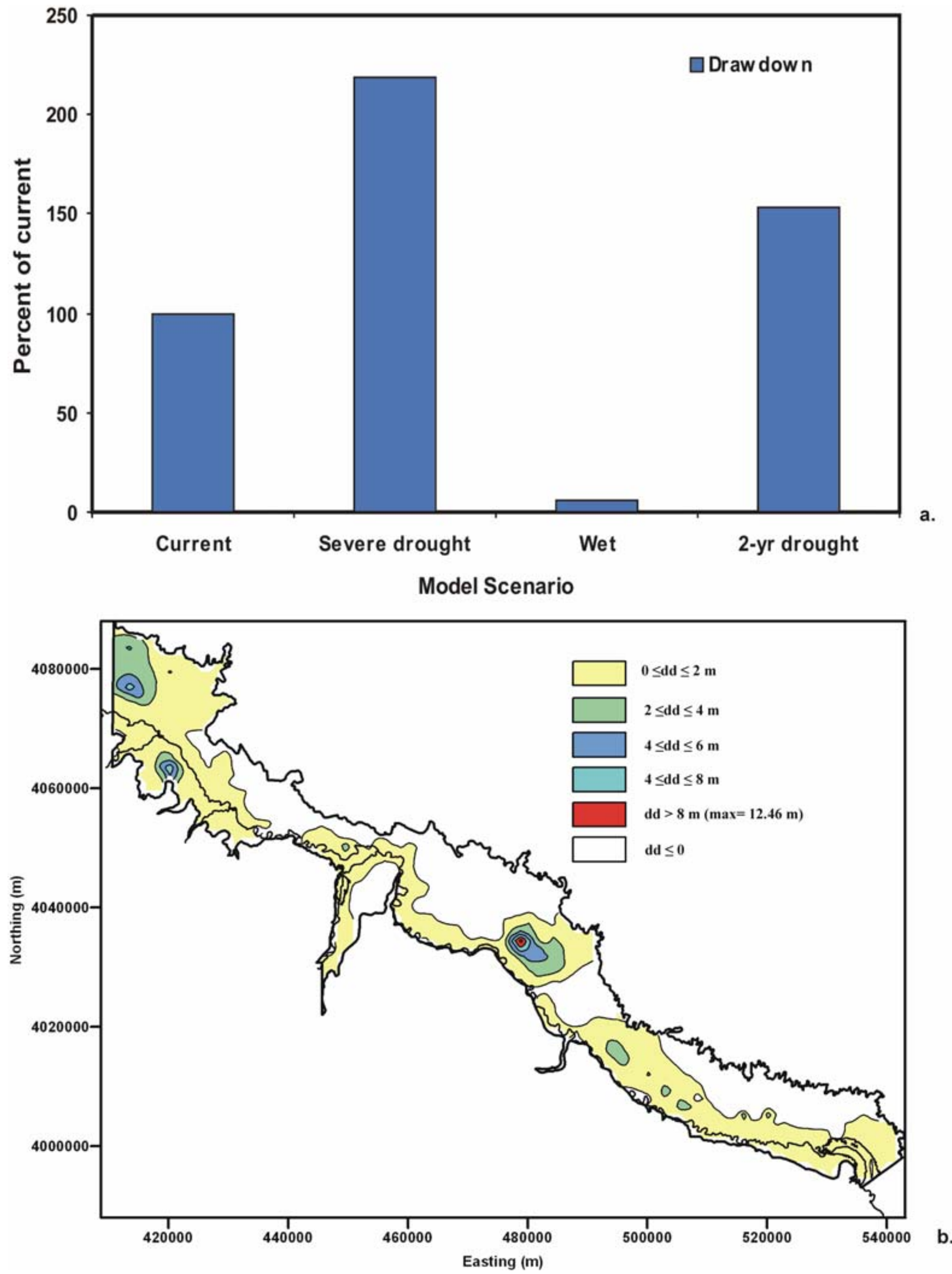

Figure 9: (a) Average drawdown under climate variability scenarios, (b) Projected aquifer saturated thickness under the severe drought scenario.

scenario. The spatial pattern looks similar to that discussed for the demand scenario at 2050 (Figure 6a), except that drawdowns, on average, are higher for the former, and the aquifer area experiencing drawdown is also increased by approximately 13%. Although, the projected groundwater withdrawal for the year 2050 under the demand scenario (the case shown in 6a) is nearly 10% more than the assumed severe drought withdrawal, average drawdowns generated by the later are higher, demonstrating the additional impact of climatic forcing.

The simulated moderate (2-yr) drought will increase the average drawdown in the aquifer by 54% over the current condition. Maximum drawdown under this scenario will be 8 m (36% less than the maximum under the severe drought). Overall, the moderate drought impact on groundwater levels will be slightly less than half that of the record drought.

As shown also in Figure 9a, should the future climate of northwestern Oklahoma change toward wetter conditions the current drawdown in the A&T aquifer will be reduced by 94%. Maximum drawdown at any point within the aquifer under this scenario will be less than 5 m.

Finally, under the human adjustment scenario, simulation results indicate that current aquifer drawdown will be reduced by approximately 12% (refer to Figure 9a).

5.6.3b IMPACTS ON AQUIFER SATURATED THICKNESS

Impacts of the simulated climate variability scenarios on aquifer saturated thickness are summarized in Figure 10a. Generally, these are similar but opposite to the impacts discussed above for water levels because of the inverse relationship that exists between drawdown and saturated thickness in a phreatic aquifer. For example, whereas the severe drought scenario will potentially increase the current aquifer drawdown by 118%, the same scenario would decrease the current saturated thickness by 92%. Similarly, the moderate drought will reduce the average saturated thickness by 27% relative to the current. Under the wet scenario however, the recovery of water levels will more than double the average aquifer saturated thickness.

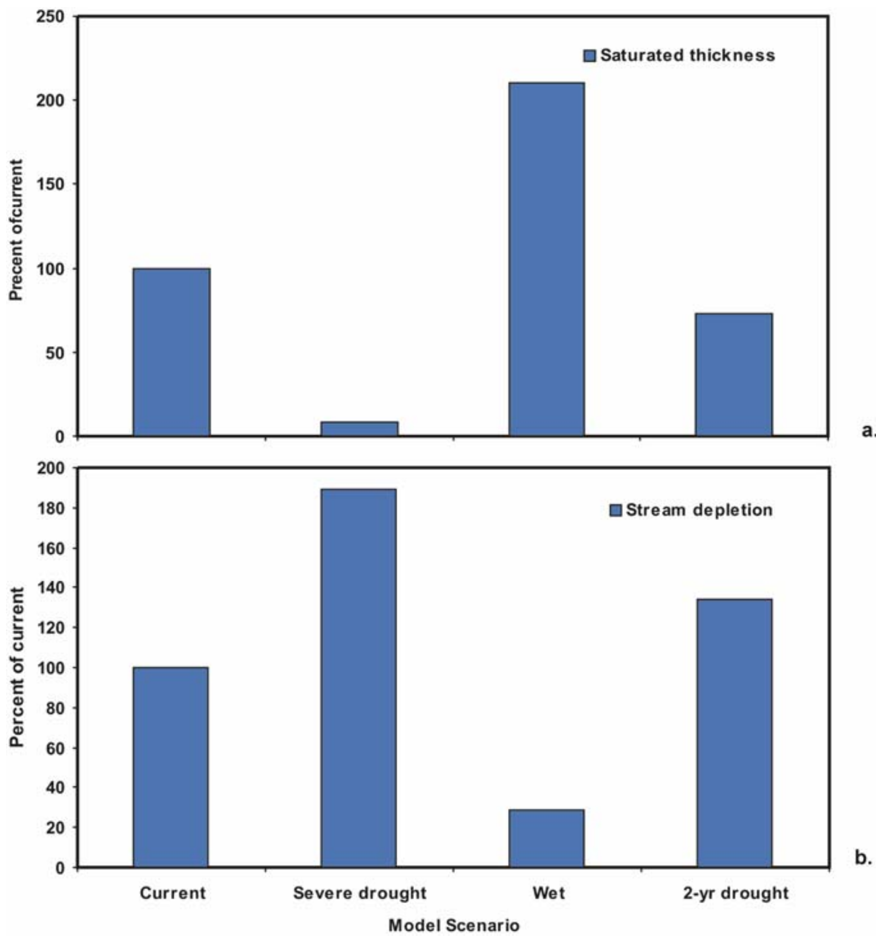

Figure 10: (a) Average saturated thickness under the climate variability scenarios, (b) simulated stream depletion under the climate variability scenarios.

6.2.3c IMPACTS ON STREAM-AQUIFER INTERACTION

As expected the worst impact on stream-aquifer interaction result from the severe drought scenario. Under this scenario, the current flow in the Beaver-North Canadian River system will be depleted by 89%. Approximately 59% of the total depletion is due to reduced baseflow. Recall that the BNCR depends heavily on baseflow contributions from the A&T aquifer; thus, the above result suggests a severe drought will deprive the BNCR, 59% of its source of discharge, leaving it a losing system. For the moderate drought scenario, stream depletion will be increased by 34% relative to the current. Again approximately 53% of the total depletion will be from reduced baseflow. Under the wet scenario, stream depletion for the current condition will be reduced by 72% due to increased baseflow and diminished stream leakage. Results of the wet scenario indicate that the BNCR system will regain its pre-development effluent status.

5.6.4 HUMAN ADJUSTMENT SCENARIO

Under the human adjustment scenario, it was assumed that future human adaptive measures to groundwater management would result to, at least, 25% reduction in aquifer withdrawal. Simulated results for this scenario are also referenced to the 2000-2004 average pumping conditions (current). The results suggest average drawdown in the aquifer will reduce by approximately 12% relative to the current conditions. As a result, the average saturated thickness will increase by approximately 9%. The impact of the 25% reduced aquifer pumping will translate to approximately 20% reduction in stream depletion relative to the current condition, compared to 72% for the wet scenario.

5.7 Summary and Conclusions

Alluvial aquifers are a critical source of water in semi arid regions throughout the world. They support human economic activities such as irrigation, domestic, and municipal water supplies as well as sustain aquatic ecological systems. However, increased pressure on these aquifers from population growth, irrigation water demand, and climate variability threatens to undermine their sustainable use. This study implemented a numerical groundwater flow model of the A&T aquifer in northwestern Oklahoma, to evaluate the potential impacts of climate variability and anthropogenic groundwater pumping on aquifer dynamics, including stream-aquifer interactions.

The results indicate that direct precipitation recharge is the primary source of inflow to the modeled aquifer (66%), and under non-pumping conditions, groundwater discharge (baseflow) to streams, constitutes the largest outflow from the aquifer (56%). Using the OWRB projected demand scenario, the study showed that average drawdown in the A&T aquifer, would range from 0.73 – 1.95 m between 2000 and 2050. However, areas of high drawdown will be localized around clusters of high intensity pumping wells. Correspondingly, the aquifer saturated thickness would decrease linearly with each decade of pumping but the overall difference between 2000 and 2050 would be less than 1m. The demand scenario would also linearly decrease baseflow with time, and induce stream leakage from overlying streams so that by 2050, baseflow would be reduced by 27% and stream leakage increased by 13%, making the BNCR a losing system beyond 2010. These results suggest the OWRB-projected pumping (demand scenario) would have a larger impact on stream-aquifer interactions compared to the drawdown picture obtained. This finding poses a lesson for aquifer investigations in general. For example, were aquifer drawdown the only focus of this investigation, perhaps, it might be wrongly concluded that the projected pumping would have little effect on long-term aquifer function when realistically, there is a substantial effect on stream-aquifer relations. For holistic aquifer management purposes therefore, aquifer studies must evaluate all areas of aquifer dynamics that may possibly be impacted by imposing stresses.

Three climatic scenarios were simulated namely, a 4-yr severe drought, a 2-yr moderate drought, and a wet period. Impacts of these climatic scenarios on groundwater levels, aquifer saturated thickness, and stream-aquifer interactions were compared with those for a normal condition; taken to be the impacts on aquifer from the 2000-2004 average withdrawals and normal recharge. Results show the severe drought for example, would create drawdowns in the aquifer ranging from 0 to 12.46 m with an average of 2.03 m, representing a 118% increase in aquifer drawdown relative to the reference condition. Such magnitude of drawdown would deplete streamflow in the BNCR system by 89%. Simulated impacts for the 2-yr drought are similar to those for the severe drought but the magnitudes of impacts are slightly less than half those for the later. Results of the wet scenario indicate good conditions for the aquifer as drawdown under the reference condition will be decreased by 94%. Under this scenario, the BNCR system will return to its pre-development gaining status. Finally, a scenario that assumed positive human adjustments in water use practices was simulated. Results suggest this condition would reduce average drawdown in the aquifer by approximately 12%. Under this scenario, stream depletion would be reduced by 20%.

Thus, results of this study have demonstrated the important influence future climate variability and anthropogenic water demand would have on the A&T aquifer.

Additionally, the results provide for water resources managers the means for evaluating aquifer management options, as well as a basis for regulating stream-aquifer relations that protect dependent aquatic ecosystems.

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Chapter 6

Summary and Conclusions

6.1 Synopsis

This dissertation used a numerical groundwater flow model (visual MODFLOW) to evaluate the response of a semiarid alluvial aquifer in northwestern Oklahoma to anthropogenic water demand and climate variability. The research is important because alluvial aquifers throughout the world are facing unprecedented pressure from a combination of population growth, agro-economic expansion, and degraded surface water quality. Alluvial aquifers have unique characteristics that permit them to serve a variety of purposes. They recharge their parent streams during non-flood periods and are critical therefore to aquatic and riparian ecosystems; they are dependable, and relatively inexpensive to exploit because the groundwater table is close to the surface. However, inherent in these advantages are reasons for concern. For example, the interaction between alluvial aquifers and overlying surface streams presents considerable management challenges in that overexploitation of these aquifers may compromise their ability to sustain flow in overlying streams and impact surface water-dependent activities as well as aquatic habitats. These concerns justify a need for evaluating the impacts of anthropogenic water demand on alluvial aquifers.

This research is timely also because it responds to increased public awareness and concerns about the possible impacts of climate variability on water resources. The potential threats to the world's water resources from global climate change have been discussed at various scales in several scientific media. It is important that resource managers and stakeholders have a holistic understanding of the issues from a practical standpoint. A study of this nature provides both the necessary background information and the results that both users and resource managers can utilize to evaluate development and management decisions. The numerical simulation method adopted has proved an effective tool for investigating aquifer dynamics. This approach has capabilities for exploring 'what if' scenarios allowing water resources planners and managers to evaluate the relative feasibility and merits of competing management options. It facilitates also planning and management, which are predominantly forward-looking processes.

Preparatory to implementing the numerical model, an in-depth analysis of precipitation and streamflow time-series at monthly, annual, and seasonal time scales was carried out for the study area using both Mann-Kendall trend test and Continuous wavelet transform methods. These analyses established the nature of the historical patterns of hydroclimatic variability. The results of the annual trend analysis, for example, showed statistically significant trends at the 0.05 probability level at 22% of the individual precipitation gauging stations analyzed. However, no trends were detected in the regionally averaged annual precipitation indicating that the observed trends are local rather than regional phenomena. Similarly, no statistically significant trends were detected in the seasonal precipitation time-series. The streamflow time series analysis showed that the Beaver River discharge experienced significant negative trends at all temporal scales examined. Because the regional precipitation has remained largely stationary, the trends in the stream discharge were attributed to groundwater overdraft and possibly land use/land cover changes; however, establishing the physical causal links was considered outside the scope of this dissertation. The CWT analysis isolated interannual and decade-scale modes of variability both in the regional precipitation and streamflow time-series. Further statistical analyses on the time series showed that about 25% of the precipitation variability in northwestern Oklahoma could be explained by variations in ENSO time series at the 0.05 probability level. Similarly, the PDO explains about 16% of the regional precipitation. These findings are consistent with other studies for the study area and in the Southern Great Plains in general. The above results facilitated both model conceptualization and the development of model predictive scenarios discussed in chapter five.

In the second study, reported in chapter four, a three-dimensional model of the study aquifer was implemented using Visual MODFLOW, a pre- and post-processor for the original USGS finite-difference model, MODFLOW. Specifically, the streamflow routing package in MODFLOW was utilized to investigate the impacts of groundwater pumping from the study aquifer on stream-aquifer interaction. The results of the study confirmed that non-flood flow in the Beaver-North Canadian River and its tributaries depends heavily on baseflow contributions from the alluvial aquifer. Prior to the onset of pumping baseflow contributed 56% to streamflow during non-flood periods, while 30% of stream leakage recharged the aquifer. This resulted in a net gain of 26% for the stream. However, pumping the aquifer over a 15-year period, decreased baseflow contribution by 29%, and raised stream leakage by 18%, for a net loss to the stream of 21%. In other words, the effect of groundwater pumping at the hypothesized scenario was to change the river from a gaining system to a losing one. Significantly however, this change (i.e. from gaining to losing stream) did not occur uniformly over the entire length of the river system. The model design and implementation permitted identification of specific stream segments that had either become gaining, losing or remained unchanged. In general, several reaches within different stream segments had changed from gaining to losing streams after 15 years of pumping. It was found that intensity of aquifer pumping as reflected in the spatial clustering of wells was the major factor driving the stream-aquifer interactions in different stream segments. One of the most important contributions of this study is that it delineates stream-aquifer dynamics at the reach and segment scales rather than average results over the entire stream-aquifer system as is the case with many studies.

Using the same model (MODFLOW), the last study (chapter five) developed upon the results of the first two to assess the impact of various scenarios of climate variability and water withdrawals on the study aquifer. Additionally, it investigated also the impacts of both climatic variability and groundwater withdrawal stresses on stream-aquifer interaction. The impact of regional water demand scenario, developed by the OWRB (demand scenario) on aquifer drawdown was investigated. The results indicated that pumping under the demand scenario would produce average drawdown in the study aquifer of up to 0.26 m meters by 2050. However, around large clusters of pumping wells, localized areas of drawdown may exceed 9 meters. Similarly, the demand scenario would adversely impact streamflow by compromising the aquifer's ability to supply baseflow to streams, while at the same time, inducing higher stream leakage into the aquifer. Specific results suggest that beyond the year 2010, the Beaver-North Canadian River would become a losing system.

The results of climate scenarios indicate that a four year drought of magnitude and duration comparable to the 1952-56 drought would result in aquifer drawdowns ranging from 0 to 12.46 m with an average of 0.68 m. This will be a 77% increase over the current drawdowns in the aquifer. Such magnitude of drawdown would deplete streamflow in the BNCR system by 57%. The simulated impacts for the 2-yr drought were similar to the 4-yr drought (discussed above) but the magnitude of impacts were slightly less than half those for the later. The results of the wet period simulation showed that such wet conditions would reduce current drawdowns in the aquifer by 94%. Under these conditions the BNCR system would remain a gaining system. Finally, a scenario that assumed positive human adjustments (defined as a 25% reduction in aquifer pumping) in water use practices was simulated. Results of that simulation indicated this condition would reduce current drawdown in the aquifer by approximately 12%. Similarly, stream depletion would be reduced by 20% relative to the current condition.

6.2 IMPLICATION FOR AQUIFER MANAGEMENT AND FUTURE RESEARCH

The overarching goal of this dissertation was to provide information about the dynamics of semiarid alluvial aquifers that can facilitate water resources planners and managers' efforts in evaluating competing management options. Information contained in chapters 3 through 5 accomplishes this goal. The trends and periodicities identified in the time series of regional precipitation and streamflow for example, has significant implication for water resources planning and development in that it paves the way for proactive planning regarding the future direction of climatic trend and impending impacts on the study aquifer. Similarly, the increased understanding of stream-aquifer relations (discussed in chapter 4) within the alluvial basin can inform a conjunctive management approach, where safe aquifer and stream exploitation limits are set in order to maintain a sustainable stream-aquifer function for human and ecological other uses. Finally, with the understanding of how semiarid alluvial aquifers respond to various intensities of pumping and precipitation inputs planners can device ways of preserving aquifer and or surface storage during wet periods. Similarly, ways of rationing withdrawal during both wet and dry periods to safeguard against total resource depletion could be sought. Programs such as artificial recharge could be experimented with.

In conclusion, the major contributions of this study could be summarized as follows:

1. From an academic perspective, this study contributes to the sparse literature on alluvial aquifers generally and so adds to our understanding of their dynamics, including how they respond to a combination of stress factors.
2. The study contributes to the on-going public and academic discourse on how to translate the possible impacts of climate variability and change into measurable sectoral indicators. This study highlights specifically climatic impacts on semiarid alluvial aquifers.
3. The understanding of alluvial aquifer dynamics afforded by this study can facilitate policy-making that ensures the rational and sustainable development and management of alluvial aquifers, particularly, in semiarid environments.