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Calibrating Northern Texas High Plains Groundwater Model

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Abstract. *In the Northern High Plains of Texas, irrigated crop production accounts for a major portion of groundwater withdrawals from the Ogallala aquifer. The concern is that diminishing groundwater supplies will severely reduce regional crop and animal production, which in turn would impact the regional economy. The objective of this study was to develop and calibrate a groundwater model for a 4-county area (Dallam, Sherman, Hartley, and Moore counties) in the Northwest region of the Texas High Plains. This study is a major component of a comprehensive regional analysis of groundwater depletion in the Ogallala aquifer region with the purpose of understanding short- and long-term effects of existing and alternative land use scenarios on groundwater changes. A comprehensive geographic information system database was developed for this purpose. Hydrologic simulations were done using MODFLOW-2000 model. The model was calibrated satisfactorily for predevelopment time by reproducing and comparing groundwater levels for the 1950s with a correlation coefficient of 0.9. Predevelopment historical groundwater levels in the 4-county study area ranged from 955 to 1,405 m above MSL and simulated levels ranged from 930 to 1,410 m above MSL. With the calibrated model, the effect of change in land use/land cover on sustainability*

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of the aquifer life will be studied. Our results are expected to be useful to develop and evaluate strategies to conserve groundwater in the Ogallala aquifer beneath Northern High Plains of Texas and improve regional water planning.

Keywords. Ogallala aquifer, water management, predevelopment, MODFLOW.

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Introduction

The Ogallala aquifer (or also named the High Plains aquifer) is one of the largest and most productive groundwater resources in the world and underlies an area of about 45 Mha in the central U.S. covering parts of Texas, New Mexico, Oklahoma, Kansas, Colorado, Wyoming, Nebraska, and South Dakota. About 66 million m^3 (or 66 GL) of water are withdrawn per day (17.5 billion gal d^{-1}) from this aquifer to meet agricultural and urban water demand (Maupin and Barber, 2005). The aquifer area is a remnant of a vast plain formed by sediments that were deposited by streams flowing eastward from the ancestral Rocky Mountains (Reilly et al., 2008). The aquifer consists mainly of hydraulically connected geologic units of late Tertiary and Quaternary age from a heterogeneous sequence of clays, silts, sands, and gravels (Gutentag et al., 1984).

In the Northern High Plains of Texas, groundwater from the Ogallala aquifer is the main source of agricultural and public-water supplies that has sustained economic development in the region for more than a century. Irrigated crop production for grain, fiber, forage, and silage, accounts for a major portion (89% - Marek et al., 2004) of groundwater withdrawals from the aquifer and the regional economy is heavily dependent on Ogallala water. It is now known that the Ogallala aquifer is an exhaustible resource. The concern is that diminishing groundwater supplies will severely reduce regional crop and animal production, which in turn will reduce the economic activity in the region. Therefore, it is essential to avoid any adverse impacts on the regional economy due to the extensive future withdrawal of the limited groundwater.

The objective of this study was to develop and calibrate a groundwater model for a 4-county study area in the Northern High Plains of Texas. The overall study is a major component of a comprehensive regional analysis of Ogallala aquifer depletion study with a purpose of understanding short- and long-term effects of existing and alternative land use scenarios on groundwater changes. In this paper, model calibration process for the predevelopment time (before 1950) is presented, understanding this period as the time when groundwater was not exploited extensively for irrigation.

Study Area

This study is geographically limited to the 4-county area in the Northern High Plains of Texas that includes Dallam, Sherman, Dalhart and Moore counties (Fig. 1). The study area shares a border with the Oklahoma Panhandle to the north and New Mexico to the west, and it occupies an area of 12,196 km^2. Groundwater exploitation in the study area is mainly for irrigation purposes following livestock and municipal uses (TWDB, 2006). About 96% of the water from wells is for irrigation, 3% for livestock, and the rest is for municipal, manufacturing, mining and steam. About 52% of total crop land (478,000 ha) in the study area is under irrigation and corn is the major crop in the region. In 2008, the study area produced about 30% of the total corn production (74.2 million bu) in Texas (NASS, 2008), and this region has one of greatest U.S. measured county-wide yield at 13.2 Mg ha^{-1} (210 bu ac^{-1}) due primarily to the region's corn being all irrigated.

Climate

The 4-county study area has an arid to semi-arid climate. Surface water availability is limited to late summer season. Precipitation increases from 381 mm yr^{-1} in the northwest to 483 mm yr^{-1} in the southeast end of the study area. Potential evaporation from free water surface ranges from 2,200 to 2,400 mm yr^{-1} exceeding precipitation and leaving little amounts of water for recharge to the groundwater system. Annual average temperature ranges from 4ºC in January

to 27ºC in July. There is no presence of major reservoirs in the study area and all waterways are non-perennial streams. Consequently, the vast majority of the area's water supply is extracted primarily from the Ogallala aquifer.

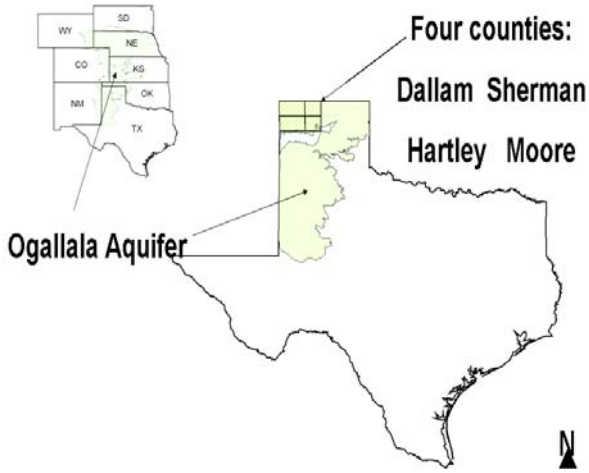

Figure 1. Four county area of the Ogallala aquifer region.

Geology

The Ogallala formation overlies Permian, Triassic, and Cretaceous strata and consists primarily of heterogeneous sequences of coarse-grained sand and gravel in the lower part, grading upward into fine clay, silt, and sand. The sands are generally tan, yellow, or reddish brown, medium to coarse-grained, moderate to well sorted, poorly consolidated to unconsolidated, although local cementation by calcium carbonate and silica occurs. The gravel is usually associated with sand, silt, and clay and is occasionally cemented (NPGCD, 2008). Ogallala aquifer is considered as an unconfined aquifer with predominant flow direction from west to east. No fractured rock zones and faults were identified in the study area. Some hydraulic continuity occurs between the Ogallala formation and the two underlying local aquifers, Rita Blanca and Dockum aquifers.

Hydraulic conductivity and specific yield are highly variable in the study area, and they do not follow any particular spatial tendency due to the dependency on sediment types, which vary widely both horizontally and vertically (Gutentag et al., 1984). Estimated hydraulic conductivity values between 8 and 120 m d^{-1} and specific yield ranges from 2.5 to 27.5% (USGS, 2008). Estimation of saturated thickness of the Ogallala aquifer in the 4-county area (Hallmark, 2008) indicates that maximum saturated thickness ranges from 15 to 140 m with an average of 50 m and depth to water ranges from 15 to 137 m. Base of the Ogallala aquifer in the study area varies in elevation from about 900 m above mean sea level (MSL) on the eastern limit of the study area to about 1,300 m above MSL in the northwest corner of Dallam County.

Materials and Methods

Database Development

Data sources included the USGS, United States Department of Agriculture (USDA), Texas Water Development Board (TWDB), and the North Plains Groundwater Conservation District (NPGCD). Most spatial and non-spatial input data for the study area came from regional studies. These data came from publications in the form of tables, GIS shapefiles and covers, and a Landsat 5 thematic mapper (TM) imagery acquired during the 2008 cropping season. All

GIS layers were projected to UTM coordinate system to facilitate overlaying to derive input data necessary for groundwater modeling. Hydrogeology in the form of shape files were used to define the aquifer base as the lower elevation for the simulated aquifer and saturated thickness to define the top elevation, creating a one layer aquifer based on these two sets of data. Spatial variability in hydraulic conductivity and specific yield were input into the model using the USGS spatial data (USGS, 2008). A digital elevation model (DEM) for earth surface was not included for MODFLOW computations, but it was used for understanding the study area for recharge areas, hydrography, and aquifer delineation. No wells were added to the model for the predevelopment period. Historical groundwater levels from observation wells and aquifer delineation (Gutentag et al., 1984) were the base for defining predevelopment groundwater levels. These historical groundwater levels were considered as the target levels to evaluate performance for this study when evaluating predevelopment time.

The hydrologic simulations were done using MODFLOW-2000 (Harbaugh et al., 2000), a computer program that solves the three-dimensional groundwater flow equation through a porous media by using a finite-difference method. A Visual MODFLOW Pro 4.3[1] (SWS, 2008) interface was used to facilitate data input and results analysis.

Conceptual Model

To assess the effects of future groundwater exploitation for water levels in the Ogallala aquifer, a conceptual model has been created to represent the actual aquifer system. Historically, groundwater in the study area was not exploited extensively until the mid 20th century, even though some wells have reported records since 1919. It is evident that the aquifer was underexploited in terms of development during that period of time, especially for irrigation in this 4-county study area. An assumption for this modeling study is that the aquifer system had steady state flow during this period of time, which is known as predevelopment time.

During wet seasons, groundwater discharged naturally by seepage to streams and springs. Discharges diminished during the dry time and natural groundwater levels remained almost constant until the next season, repeating the cycle. According to this assumption, during the first half of the 20th century, the aquifer can be considered as behaving naturally, obtaining recharge from precipitation and withdrawing water by means of evapotranspiration (ET) from plants, stream leaking, and spring discharge and therefore keeping groundwater levels stable.

Data for geological characterization of the conceptual model were obtained from the USGS and updated with published reports on hydrogeology, topography, vegetation, soils, hydrography, climate and additional information available for the region. Calibration of the model, to verify the performance of the conceptual model, included computer simulations under different scenarios to match historical conditions by means of parameter modification and conceptual model adjustment. Although the object of interest for modeling groundwater hydraulics was the Ogallala aquifer in the 4-county study area, boundaries were defined beyond these political boundaries to reduce inaccuracies in the study area boundary. Consequently, boundaries for computer modeling (Fig. 2) were extended to aquifer boundaries in the vicinity, making the conceptual model more realistic at the county boundaries in Texas.

A computer model was created for the study area based on a grid that matched an imagery pixel size of 400 m by 400 m. Each pixel had internal, uniform characteristics for computing purposes. Therefore, each and every cell in the grid had its own parameter values, which were

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[1] Mention of trade names or commercial products in this article is solely for the purpose of providing information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

used for defining aquifer characterization over time, and as a consequence, they changed through time. Even though the aquifer was thought to be vertically homogeneous in the study area, the aquifer was divided into ten layers to make the computational process more efficient. This sub-division did not affect the conceptual model per se, but allowed the computer to pass data from place to place in a smoother way than having a one-layer model. Thus, cell computation was done by a tenth of the aquifer thickness and results were subsequently merged for analysis as a whole entity.

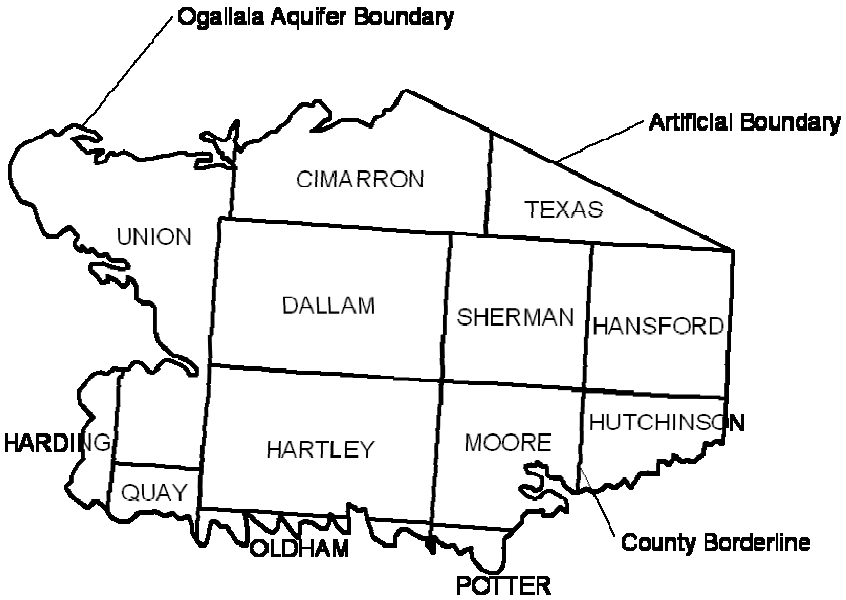

Figure 2. Computer Model Boundaries and counties in the study area.

Based on the historical information, springs were added to the study area with the purpose of recreating predevelopment conditions. Historical data on springs for modeling during the predevelopment time was obtained from Brune (1975). In Dallam County, one moderately large spring found in the 15th century (0.28 to 1.0 $m^3 s^{-1}$) had become a medium-size spring (0.1 to 0.03 $m^3 s^{-1}$) by 1973. In Hartley County, a small spring in the 15th century (0.003 to 0.0003 $m^3 s^{-1}$) was reported as a “former spring” by 1973, meaning that it disappeared (stopped flowing). A medium size spring reported in Oldham County was classified as a small spring by 1973. There are no major springs currently in the 4-county study area.

Precipitation over the study area is a key element for recharge evaluation. Soil types and the effect of ET over the recharge areas were evaluated. However, ET was not computed separately because the water table was much deeper than plant root zones and it was assumed that they were unable to extract groundwater. Instead, it was considered that ET effects above the recharge areas were included in computations by assuming that recharge was a percentage of precipitation. From here on, the term recharge should be interpreted as net recharge that includes evaporation from the soil surface and transpiration from plants. Recharge was applied to the uppermost active layer of the model in all cases.

Pumping for irrigation purposes is the primary mechanism used for aquifer discharge as precipitation is the main mechanism for recharge, the latter representing a small proportion because of the effects of evaporation from the soil and transpiration from plants. A detailed study for the region by Luckey and Becker (1999) recommended recharge rates of 16 to 24 mm

yr^{-1} for sand dune areas in Dallam and Hartley Counties and rates from 1.6 to 2.1 mm yr^{-1} for low permeability soils in Sherman and Moore Counties. More recent groundwater modeling studies (Dutton, 2004; Dutton et al., 2001) of the Ogallala "n" model showed the necessity for increasing recharge rates in some areas on Dallam and Hartley Counties up to 10 mm yr^{-1} and on Sherman County up to 4 mm yr^{-1}.

Boundary Conditions

The computer model was extended beyond the political boundary to reach the western Ogallala aquifer borderline (Fig. 2) in order to make the model more robust. This was accomplished by having to increase computing time. The aquifer borderline and part of the straight line modeling border located to the north were assimilated to a no-flow boundary. A general dependent flow boundary corresponds to a cell that transmits flow, to or from, an external source proportionally to the head difference between the cell and the head assigned to the external source. For the eastern boundary and a portion of the northeast modeling border straight line, a general head dependent flow was defined using different heads and distances to the external source depending upon the nearness to historic water table elevations. Criterion applied to define distances from the study area boundary to the general head dependent source was three times the average depth of the aquifer in the boundary area.

Once the conceptual model was defined, model calibration was required to verify that output from the model corresponded to situations that matched the historical natural aquifer behavior. For calibrating the model for predevelopment time, a steady-state simulation was set to keep all boundary conditions constant through time.

Results and Discussion

Groundwater levels for predevelopment time were reproduced satisfactorily by simulating the groundwater levels in the Ogallala aquifer in the 1950s, with a correlation coefficient of 0.9. Predevelopment historical groundwater levels ranged from 955 to 1,405 m above MSL and simulated levels ranged from 930 to 1,410 m above MSL in the 4-county study area (Fig. 3). In general, high groundwater levels presented less irregular distribution than low groundwater levels. It is noteworthy to mention that predevelopment historical groundwater levels were estimated for a regional study (Gutentag et al., 1984) and they should be treated as guidelines. However, when comparing historical data to simulated groundwater levels, areas of over-prediction were located in the northern part of Sherman County and in the northeast corner of Dallam County. Areas of under-prediction of groundwater levels were located throughout Moore County and the eastern part of Hartley County.

Coarser contour lines were observed for simulated groundwater levels due to more detailed information used for this study than for the historic levels. The anomaly in the Hartley-Moore County boundary was generated because the aquifer base was more elevated in this part of the study region than in the surrounding area.

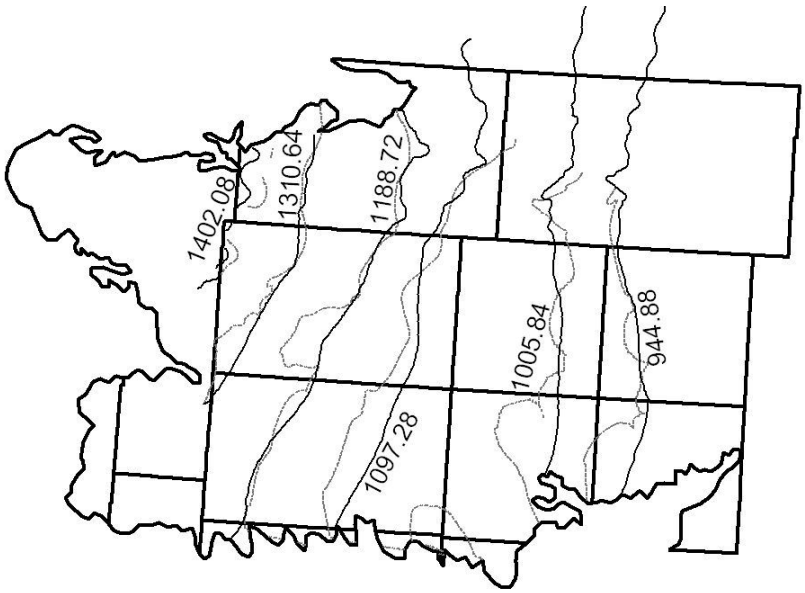

Figure 3. Simulated (thinner lines) and Historical Water Levels for Predevelopment in meters.

Summary

A groundwater model for a 4-county study area in the northwestern Texas High Plains of the Ogallala aquifer region was developed and calibrated for predevelopment conditions. A comprehensive Geographic Information System (GIS) database was developed for Dallam, Sherman, Hartley, and Moore Counties in Texas. Hydrologic simulations were conducted to calibrate the groundwater model against historical data for accuracy during the predevelopment period. A Visual ModFlow Pro 4.3 software was used as an interface for MODFLOW to facilitate data input and result analyses. Preliminary results indicate that simulated groundwater levels closely followed trends in the observed historical groundwater levels of the Ogallala aquifer in the study area. Future modeling efforts should include model calibration for post-irrigation development years and evaluation of the effect of change in land use/land cover and other cultural practices on sustainability of the aquifer life within the study region.

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