# GIS-Assisted FEFLOW Modeling of Groundwater Moving Processes within the Minqin Oasis in the Lower Reach of the Shiyang River, Northwest China

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*Abstract*— **Oases are specific landscapes and play very important economic roles in arid Northwestern China. Yet, the peripheral ecological systems around the oases are equally important to the oasis economic systems in terms of protecting the oasis from desertification and ensuring sustainable development of oases. However, the rapid increases in the population and steady progress in the society and technology since 1950s have greatly expanded irrigated agricultural production in the oases, resulting in a dramatic decrease in stream flow and associated increase in the groundwater withdrawal in arid Northwestern China. The overexploitation of groundwater formed groundwater table depletion cones and eventually lowered the groundwater table not only in the oases but also in the periphery of the oasis, resulting in an overall decrease in soil water content. In response to the soil moisture decrease in the periphery, some plant species relying on groundwater resource have been dying out and other more mesic species have been replaced with more xerosere species. In this paper, the groundwater flowing processes and the water-table fluctuating processes during the past 40 years were simulated to obtain the spatial and temporal distribution of groundwater table by means of the GIS-assisted FEFLOW modeling based on the hydrogeologic data obtained in the Minqin Basin. Several conclusions can be drawn from the simulated results. First, the discharge and recharge of groundwater retained balanced and the groundwater table depth in the periphery area of the oasis maintained 2-3 m deep during 1960-1965. Second, the utilization of the groundwater dropped the groundwater table within the oasis to 5-10 m, leading to the formation of big groundwater depletion cones that started to influence the groundwater table of the periphery area in the 1970's. Third, the further overexploitation of the groundwater within the oasis has dropped the groundwater table to 10-20 m in the oasis and 7-10 m in the periphery since the middle 1980's.**

***Keywords-The Minqin oasis; periphery of oasis, Groundwater fluctuation; FEFLOW; Modeling; groundwater depletion cone;***

## I. INTRODUCTION

Oases are specific landscapes that exist within deserts in arid regions (Jia et al. 2003). The oases in the arid Northwestern China take up only 4–5% of the total area of the arid regions, but, over 90% of the population and over 95% of the social wealth are concentrated within the oases. In general, oases located in the middle and lower reaches of the inland rivers are hydrologically supported by the river-recharged groundwater that lies within the underlying alluvial sediments. As a part of the arid Northwestern China, the Hexi corridor is also embedded with oases and the oases in the corridor have been playing very important political and economic roles during the past over 2000 years since Han Dynasty (Han, 2001). However, the rapid increases in the population and steady progress in the society and technology since 1950s have greatly expanded irrigated agricultural production in the oases, resulting in a dramatic decrease in stream flow and associated increase in the groundwater withdrawal. Consequently, water resource has become an obstacle to the development of agricultural production, leading to an increasingly severed conflict between supply and demand of water resource. As an extreme example of the conflict occurring in the Hexi Corridor, the Minqin Basin that lies in the lower reach of the Shiyang River has been both economically and ecologically suffering from the decrease in the stream flow due to upstream water interception and local groundwater overexploitation. The surface water resource into the basin is solely supplied by the Shiyang River (one of the three inland rivers in the Hexi corridor), which is in turn supplied by natural precipitation and ice-snow melting in the Oilian Mountains in the eastern margin of the Qinghai-Tibet Plateau. Specifically, the stream flow coming to the Hongyashan Reservoir that supplies irrigation water to the Minqin oasis has decreased from $4.5\times10^8$ $m^3$ to $1.14\times10^8$ $m^3$ due to upstream water diversion to irrigation (Gao, 2003) and at the same time the irrigated acreage in the oasis has been greatly expanded. Consequently, the groundwater within the oasis has been excessively extracted since 1970, leading to the formation and expansion of the groundwater table depletion cones (E et al.1997; Ding et al. 2003). The coalescing of the individual depletion cones has not only drastically lowered the groundwater table within the oasis but also the groundwater table in the periphery of the oasis, resulting in an overall decrease in soil water content. In response to the soil moisture decrease in the periphery, some plant species relying on groundwater resource have been dying out and other more mesic species have been replaced with more xerosere species (Yang, 1999). As we all know, the desert plants distributed in the periphery of the oasis play the most essential roles to protect the oasis from desertification, meaning that the oasis economic systems have to co-exist with

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the peripheral ecological systems in the Minqin Basin. In order to develop the strategies of retrieving the vegetation and preserving the oasis, this study is designed to investigate the groundwater flowing processes and the water-table fluctuating processes during the past 40 years to obtain the spatial and temporal distribution of groundwater table by means of the GIS-assisted FEFLOW modeling based on the hydrogeologic data obtained in the Minqin Basin.

## II. STUDY AREA

The Minqin Basin (103° 02'- 104° 02′ E and 38° 05′ - 39° 06′ N), covering an area of $1.6\times10^4$ km$^2$, lies in the lower reach of the Shiyang River with an elevation from 1310 to 1900 m above sea level and the Minqin oasis is located in the center of the basin accounting for 6.9% of the total basin. The oasis, flanked by uninterrupted hills along northern and southeastern borders and scattered hills in southern border of the basin, is an irrigated agricultural system.

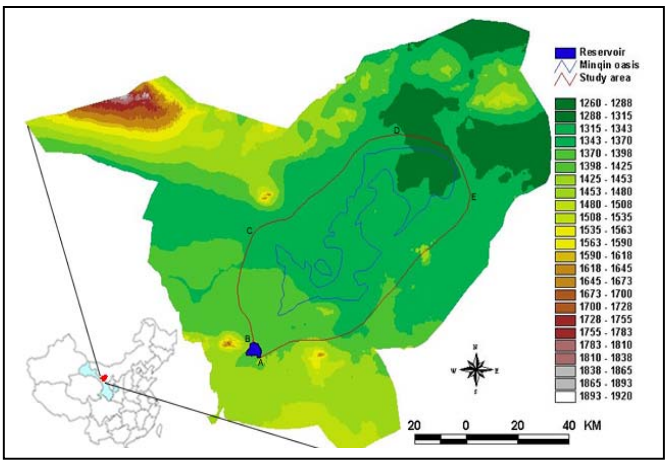


Figure 1. Location of the study area in the Minqin Basin

The study area located in the plain of the Minqin Basin (see Figure 1), covering an area of 4017km$^2$, has a typical arid continental climate with an average annual temperature of 7.6 ℃ (average maximum: 30.7℃ in July and average minimum: 16.8℃ in January) and an average annual precipitation of 114.4 mm (1960-2002). Precipitation, about 80% occurring between June to September, is characterized by a high variability (a maximum of 185.1mm in 1973 and a minimum of 42.2mm in 1962) with an annual potential evaporation of about 2604.3 mm. The average annual wind velocity is 2.2ms$^{-1}$ with a prevailing wind direction of NW (Yan, 1997).

The study area slopes gently northward from 1400 m to 1310 m above sea level with a mean surficial gradient of 0.05-0.09%. The Hongyashan reservoir is situated at the southern end of the study area (The arc of AB seen in Figure 1 is the dam-base of Minqin reservoir, BC is the drainage divide of Minqin Basin, CD is the northern hills foot line, AE and ED is south-east border along the topography). In addition, two hills named Suwu Mount and Langpaoquan Mount outcrop the chalky limestone in the south and north respectively and do not participate in any groundwater processes.

## III. THE GROUNDWATER-FLOW SYSTEM

### A. Hydrogeological structure

The borehole logs of the study area along the course of the Shiyang River investigated by Gansu Provincial Hydrogeologic Bureau (GPHB) reveal that the sequences of the sedimentary formation contain several superimposed sub-aquifers separated by semi-impervious or impervious aquitards and are comprised of Quaternary sediments of lacustrine sands, silts and clays. To implement our modeling effort, we simplify the hydrogeologic complex into two aquifers separated by a clay aquitard based on the findings of the borehole logs. The top hydrostratigraphic unit is considered to be a sandy unconfined aquifer up to 150 m thick in the south and to 120 m thick in the north. The top unconfined aquifer, intercalated with thin clay lenses that may give rise to localized perched groundwater bodies, is the dominant groundwater-withdrawing formation because 90 percent of the wells are extracted from it for irrigation. The second aquifer underlying the 30-50 m thick clayey aquitard and overlying the Eocene formation has a thickness of 100 m.

### B. Groundwater flow system and the mechanisim of recharge and discharge

The Hongyashan Reservoir dammed the Shiyang River in 1960, and the artificial channels have replaced the natural channels since 1961 in the Minqin oasis. The seepage flow runs along the gravity gradient with a N-S direction. The recharges into the aquifer of the Minqin Basin include horizontal lateral flux from the south aquifer and vertical infiltration from the rainfall and the seepage from irrigation water. The amounts of the vertical infiltration from the rainfall decrease with the withdrawal-caused water-table decline. For example, the average infiltration rate is 16.8 mm·a$^{-1}$ when groundwater table depth is less than 5 meters, while the rate is 0 mm·a$^{-1}$ when the depth is more than 5 meters (Ma, 2002). The sum of infiltration from irrigation water is calculated to be $3.0\times10^8$ m$^3$ in 1960-1965, $2.6\times10^8$ m$^3$ in 1970, and $2.2\times10^8$ to $1.8\times10^8$ m$^3$ from 1980 up to now. Investigations by GPHB revealed that the lateral flux through the dam-base is around $6.0\times10^6$ m$^3$a$^{-1}$. The lateral flux from the southern aquifer is about $4.0\times10^7$ to $5.0\times10^7$ m$^3$a$^{-1}$.

The water discharges include actual evapotranspiration from the shallow unconfined groundwater, the net withdrawal of groundwater and some lateral discharge outputs. The evapotranspiration is directly related to the depth of the groundwater table. For example, the evaporation is 148 mma$^{-1}$ when the groundwater table ranges between 1 to 3 m, while it becomes 17 mma$^{-1}$ when the groundwater table ranges between 3 to 5 m and 0 mma$^{-1}$ when the groundwater table is more than 5 m. The pumping of groundwater began in 1965 in the Minqin Basin, but the number of pumping wells increased dramatically from 1970 to 1979 and reached 7000 and has maintained unchanged 8000 since 1980 (see Table 1). The wells are irregularly distributed within the oasis. In addition, the pumping wells have been deepened from 20～30 m to 60～150 m in the past 40 years. It should be noted that the lateral discharge out of the study area might be negligible considering the decline of groundwater table (Ma, 2002). The budget of groundwater (see Table 1) was calculated for Model designing.

TABLE I. THE BUDGET OF GROUNDWATER ($1\times10^8 M^3$)

| Years | Number of wells | Recharge | Discharge | Net Consumption |
|---|---|---|---|---|
| 1960 | 0 | 5.0 | 5.0 | 0 |
| 1965 | 100 | 4.0 | 4.5 | 0.5 |
| 1970 | 1000 | 3.5 | 5.0 | 1.5 |
| 1979 | 7000 | 3.0 | 5.6 | 2.6 |
| 2000 | 8000 | 2.0 | 6.0 | 4.0 |

## IV. METHODOLOGY

### *A. Numerical model and design of boundary conditions*

The employed numerical model is FEFLOW, a finite element code based on the general three dimension (3D) form of the governing differential equation for flow in heterogeneous isotropic media, allowing for the usual Dirichlet (specified head) and Neumann (specified flux) boundary conditions (Beckers, 2001). The Bouseeinesq differential equation described below is the principal functions in it.

$$\frac{\partial}{\partial x}\left(Kh\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kh\frac{\partial H}{\partial y}\right)+W(x,y,t)=\mu\frac{\partial H}{\partial t} \qquad (1)$$

$$H(x,y,t)|_{t=0}=H_0(x,y) \qquad (x,y)\in D \qquad (2)$$

$$\frac{\partial H}{\partial n}|_{\Gamma_2}=q(x,y,t) \qquad (x,y)\in\Gamma_2 \qquad (3)$$

Where H is the saturated hydraulic head [L], h is the water table elevation above the impermeable barrier [L], $H_0$ is the initial hydraulic head [L], q is the flux to recharge [$LT^{-1}$], K is the hydraulic conductivity [$LT^{-1}$], $\mu$ is the specific yield, W is the water balance, i.e., discharge minus recharge [$LT^{-1}$], D is the study area, $\Gamma_2$ is the second kind boundary condition, t is time [T] and *n* is the normal direction.

The model of FEFLOW is composed of three parts: 1) The designation of finite element mesh; 2) 3D designation of slices and layers; and 3) Problem editor to specify the parameters needed for simulation.

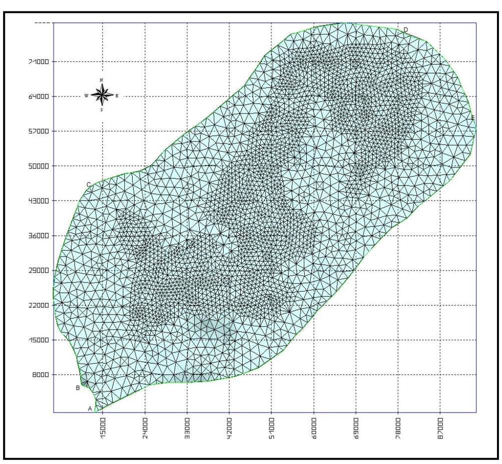

Figure 2. Finite element meshes in horizontal plane.

The model area is divided into 18051 mesh elements containing 12376 mesh nodes. The meshes are refined in the oasis to consider the highly varying hydrogeological properties of oasis (see Figure 2). To consider the vertical variability in the hydrogeological properties for 3D simulation, the formation is simplified into 2 aquifers separated by a clay aquitard as described above. The real world z-elevation of 4 slices of the 3 layers was defined respectively in the DATA REGIONALIZATION function on the basis of the modeling-area digital elevation model (DEM) prepared in ARCVIEW. The necessary data for each slice of the 3 layers were assigned, i.e. flow initial conditions such as hydraulic head, flow boundaries such as the second and fourth kind boundary conditions, and flow materials such as hydraulic conductivity, specific storage coefficient and porosity of the formation.

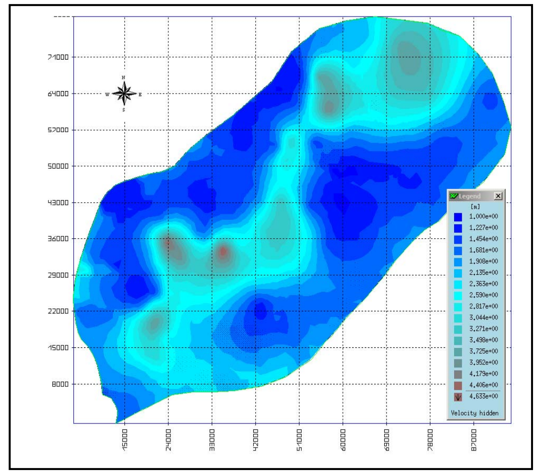

Figure 3. Distribution of groundwater table depth in 1960

The initial hydraulic head of groundwater surface in 1960 was assigned (see Figure 3) by means of interpolation of imported so-called ‘triplets file’ function. The second kind boundary condition (Neumann) was adopted in the model (see Figure 2) where AB with 0.08219 $md^{-1}$, AE with 0.01369 $md^{-1}$ of flux and BC-CD-DE with zero flux. The fourth kind boundary condition (wells), which is the net consumption that causes the drawdown of groundwater table, was assigned from 1960 to 2000 according to the Time-varying Power function that can edit or import the net groundwater consumption rate data (Table 1). The net consumption was calculated based on the budget of recharge and discharge. It should be noted here that in terms of discharge, the evapotranspiration dominated the earlier period while the groundwater pumping later period. The saturated conductivity and storativity (drain/fillable porosity) of 3 layers (upper aquifer, aquitard and bottom aquifer) were assigned respectively in the Flow Materials Function, in which the parameters of flow materials derived from the borehole logs investigated by GPHB were prepared in ARCVIEW. In order to calibrate the model, the data of 28-referenced observation points (wells) in refined area of the oasis were utilized.

After assigning all parameters needed for simulating, we set the constant time of 480 steps with the step length of 30 days.

### *B. Calibration of the mode*

The calibration of a complex groundwater model is normally a time-consuming but an essential task (J. Beckers and E. O. Frind, 2001). Modeling calibration is the process of adjusting model parameters and comparing the results until calculated head values closely match the recorded values within a pre-established range of error at selected points of the upper aquifer (Roger González-Herrera, 2002).

In this study, the data of 28-refenrenmced observation wells recorded from 1982 to 2002 with monthly resolution was used to compare with the simulated groundwater table depth through adjusting the following parameters: the recharge flux of the second kind boundary condition, the time-dependent amounts and distribution in the Minqin oasis of pumping groundwater, and the flow materials of saturated conductivity and the storativity (drain/fillable porosity) by trial and error.

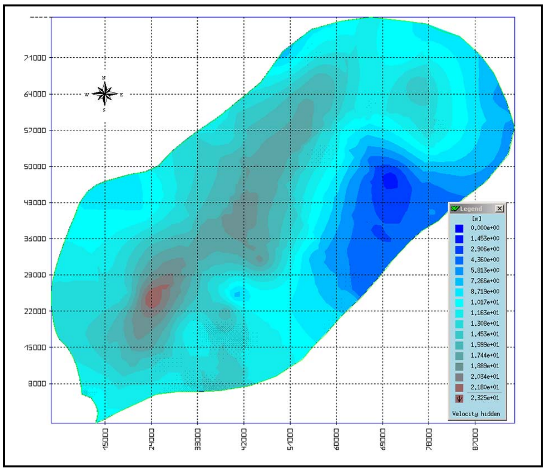

Figure 4. Distribution of groundwater table depth in 2002

The distribution of simulated groundwater table depth in 2000 (14400$^{th}$ day) was shown (see Figure 4) and the average error of simulated value is 0.5 m in comparison with the observed data (See Fig. 5).

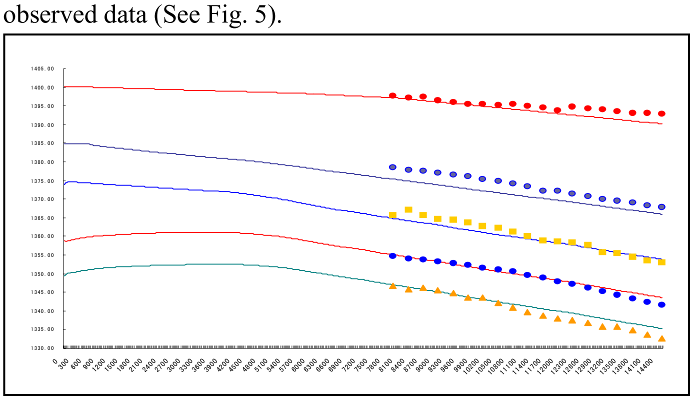

Figure 5. The groundwater table comparison between observed and simulated values in the selected 5 wells: ······Observations, —— simulations.

## V. DISCUSSION AND CONCLUSIONS

The development of the Minqin oasis through pumping groundwater has been impacting the ecosystem of its periphery region and is going to threaten the safe existence itself. The simulation of groundwater table for the periphery of the oasis where there are little observed records available makes it possible to quantitatively investigate the relationship between the drawdown of groundwater table and the vegetation degradation in the arid inland river regions. Several preliminary conclusions can be drawn from our simulation. First, the discharge and recharge of groundwater retained balanced and the groundwater table depth in the periphery area of the oasis maintained 2-3 m deep during 1960-1965. Second, the utilization of the groundwater dropped the groundwater table within the oasis to 5-10 m, leading to the formation of big groundwater depletion cones that started to influence the groundwater table of the periphery area in the 1970's. Third, the further overexploitation of the groundwater within the oasis has dropped the groundwater table to 10-20 m, causing the groundwater depletion cones to reach the periphery of the oasis and the groundwater table of the periphery has been consequently lowered to 7-10 m below the surface since the middle 1980's.


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