Estimation of the groundwater exploitation based on Land Subsidence numerical model: A case study in the plain area of Tianjin

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Abstract. Historical data about withdrawal of regional groundwater serves as a foundation for better evaluating and scientifically managing the groundwater resource. However, due to limitations of management system and workload etc., statistical data shows that groundwater exploitation is much less than what we expect in fact. In this study, we take the plain area of Tianjin as an example, the historical dataset on groundwater withdrawal is estimated reversely based on the coupled numerical model-groundwater flow and land subsidence via Modflow2005. Specifically, pumping rate serving as an input in the model is continuously modified until the numerical head distribution simulates observed value at every county in a specific period. Nonetheless, the pumping rate is also constrained by the value estimated by statistical method and quota method. Finally, the mean annual value of groundwater exploitation during 1998 to 2008 is estimated to be $8.35\times10^8 m^3/a$.

Introduction

Investigation of groundwater exploitation is viewed as a main task and a key index for the accurate evaluation of groundwater resources as well. At present, investigation of groundwater exploitation still adopts traditional methods, such as water meter measurement method, quota method, and "mu times" method in terms of different statistical methods and calibers and accordingly leads to relatively big error as a result. It is revealed from the United States Geological Survey's report about estimated ground-water withdrawals from the Death Valley regional system that according to traditional estimation method, estimated data on mining water, public utilities water, and domestic water use is slightly different from the statistical data, but the estimated data on irrigation use is greatly different from the statistical data. Of which, the biggest uncertain factor is the application rate [1]. In China, the water use in agriculture makes up very large proportion of the groundwater exploitation. According to the Ministry of Water Resources of P. R. C's 2008 Water Resources Bulletin Data, agricultural use of groundwater in Haihe River Basin accounts for nearly 70% of its total groundwater use. Such a data error exerts severe influence on the precision of regional groundwater resource evaluation, prediction of groundwater regime, and creditability of the scientific utilization and planning. That accordingly inflicts the groundwater resource's unreasonable allocation and inappropriate exploitation, as well as brings about problems to the quantitative management of groundwater exploitation and utilization.

One of the groundwater flow model's important functions is to identify the hydrogeological condition. Long-series and relatively consummate groundwater monitoring data could do a favor for the establishment of the groundwater numerical model. At present, China and overseas countries have launched massive study on the land subsidence numerical model under the groundwater exploitation condition [2-4]. In view of the slow drainage of aquitard, X.-D. Cui established the "Coupled groundwater flow and land subsidence modeling " for Tianjin downtown ($546km^2$) [5], and the Antelope Valley Model [6] and San Joaquin Valley Model [7] typified the simulation of land subsidence by using the subsidence module on the basis of MODFLOW. In addition, combination of the TOUGH2 and ABAQUS software offered especial method for the study on the simulation of land subsidence in the Wairakei-Tauhara region [8]. Moreover, the land subsidence model that was established by modifying the Merchant Model mirrors all-round considerations on the soil deformation's characteristics and stratum structure's complexities [9].

In this paper, we take the plain area of Tianjin as the research target and take fully into account the land subsidence resulting from groundwater exploitation. As a result, we establish the "Coupled groundwater flow and land subsidence modeling". In the plain area, we complete lots of hydrogeology and engineering geology work, and acquire relatively reliable and accurate hydrogeological parameters, which lay a foundation for us to take advantage of the groundwater monitoring data (groundwater level and land subsidence value etc), refer to traditional statistical method, and make use of numerical model to estimate and revise the groundwater exploitation, as well as make possible the acquisition of relatively reliable exploitation data.

Land subsidence numerical model

Located in the lower reach of Haihe Basin, the plain area of Tianjin has a floor space of $1.06\times10^4 km^2$. In this area the quaternary aquifer systems fall into six aquifers in a top-down sequence. As the main water source in this area, the groundwater has been overexploited for a long time, which accordingly resulted in the subsidence of a large area of plain in the south of the Baodi Fault. By 2002, the land subsidence area had amounted to $0.88\times10^4 km^2$. To further learn about the correlation between the groundwater exploitation and the land subsidence, we utilize the United States Geological Survey's groundwater flow simulation program MODFLOW 2005 and the land subsidence simulation package-SUB [10] to establish the regional "Coupled groundwater flow and land subsidence modeling " [11].

In the model, the groundwater flow in the study area is considered as three-dimensional fluid flow in porous media, and the land subsidence is considered as vertical one-dimensional deformation. In addition, the aquitard with thickness of not greater than 1.5m is classified as no-delayed yield aquitard, and that with thickness of greater than 1.5m is classified as delayed-yield aquitard which will be processed by diffusion equation of double-sided drainage. According to the groundwater head of the aquitard and volume of groundwater released from the aquitard, the groundwater flow model and land subsidence model will be coupled. Also, we adopt the 500m×500m rectangular grid to subdivide the entire simulative area, and take the period (January 1998 to December 2008) as the model calibration and verification period, during which, each month is regarded as a stress period. We also classify the source and sink items of groundwater in the study area into three factors (i.e., point, line, and surface), as well as conceptualize these items as the well in the unit of township and allot them into different grids of the study area.

Estimation on Tianjin's groundwater exploitation

Current exploitation situation. From 1991 to 2003, the average annual groundwater exploitation in the plain area of Tianjin was $7.10\times10^8 m^3/a$. Therein, the groundwater exploitation in northern parts (like Baodi District, Wuqing District, Jixian County, and Ninghe County) was the maximum, and that in downtown and Tanggu District was the minimum. In Tianjin, the average groundwater exploitation intensity was about $6.59\times10^4 m^3/a\cdot km^2$, of which, the exploitation intensity in the fresh water area hit $14.87\times10^4 m^3/a\cdot km^2$. In northern parts of Tianjin, groundwater of I and II aquifers was mainly exploited. In Jixian County and Baodi District, mixed exploitation was mostly adopted for I and II aquifers in the fresh ware area. On the contrary, II and III aquifers were mainly exploited in the saline water area, and the average annual groundwater exploitation in these two aquifers respectively made up 35% and 33% of the saline water area's total exploitation. Besides, the groundwater exploitation of IV and V aquifers in central and southern parts also accounted for relatively large proportion [12].

It is revealed from investigation and statistics that in 2003, the groundwater exploitation in plain area of Tianjin was $6.87\times10^8 m^3/a$, of which, agricultural use made up 60.10%, domestic use and industry use respectively accounted for 22.03% and 17.87%. In the fresh water area, the exploitation intensity was relatively large. For instance, the exploitation intensity in plain area of Jixian County and Hangu District hit $15.88\times10^4 m^3/a\cdot km^2$ and $11.40\times10^4 m^3/a\cdot km^2$ respectively. In addition, number of intact motor-pumped wells attained 3.03×10^4, and density of motor-pumped wells (9.8 wells /km^2) in Jixian County was the largest, but the average density of motor-pumped wells in Dagang District was less than 1 well/km^2.

Due to different reasons, the statistical data has a big difference from the volume of actual groundwater exploitation, and so this study is in an effort to estimate the groundwater exploitation of past years in the study area by virtue of the method of calibration and verification of the coupled model.

Existing data. At present, there are statistics data and "Quota Method" data [13] on the groundwater exploitation in the plain area of Tianjin. Regardless of a big difference from the statistical data and lots of influential factors for quota method, the quota method still serves as the foundation of this study. Since the statistical data on exploitation in 2006, 2007, and 2008 are detailed and sufficient, and the statistical data is recorded by different aquifer units and types, the annual value of groundwater exploitation of the three years will be taken as the model's initial value in corresponding period. In other periods, we will take data from the quota method as the model's initial value. That will not just verify original statistical data, but also evaluate the precision of the quota method.

In this study there are lots of observation wells for the deep groundwater's water level. Of which, II-VI aquifers respectively have 136, 87, 53, 42, and 4 water level long-observation wells, and the six groups of land subsidence markers are involved in the simulation. In addition, there are datasets of simultaneous measurement of groundwater level in 1997, 2000, 2005, 2006, 2007, and 2008, and these data are considered as the most fundamental and intuitionistic data for estimating the exploitation by the model. Due to this, their precision will directly affect the precision of the estimation.

Estimation method based on the model. When the groundwater is being exploited, change of water level is the most direct result. On the ground of this, we estimate the annual value of groundwater exploitation by fitting the calculated water level and the observed water level, with steps as follows (fig.1):

(1) Equipotential water level is depicted via Kriging method using historical observed dataset. While arithmetic averaged value of each aquifer within a specific township is calculated by averaging the assigned value derived from Kriging method.

(2) Initial value of water level in this model is specified by using value derived from statistical and quota method. Other inputs such as hydraulic conductivity, sinks and sources are treated as a specified value. Output such as water level at each stress period is extracted by using Micro code in EXCEL2007, which is utilized to estimate calculated arithmetic averaged value of each township at every aquifer.

(3) Comparison between observed and calculated arithmetic averaged water level is conducted in ACCESS2007. The case when calculated value is higher than observed value implies greater magnitude of withdrawal is expected in fact rather than the valued specified, and vice versa.

(4) According to the heterogeneity of hydrogeological properties such as specific yield (phreatic water) and specific storage (confined water), we determine the increase or decrease in magnitude of exploitation , and the formula goes as follows:

$$\Delta Q_i^j = \begin{cases} 10^6 (H_i^j - h_i^j)\cdot \mu_i \cdot A_i & When\ j = 1, \text{namely, phreatic aquifer} \\ 10^6 (H_i^j - h_i^j)\cdot \mathrm{M}_i^j \cdot \mathrm{S}_i^j \cdot A_i & When\ j = 2 \sim 6, \text{namely, the confined aquifer} \end{cases} \quad (1)$$

In above formula, *i* refers to the i^{th} township, *j* refers to the j^{th} aqifuer (*j*=1,…,6), and ΔQ_i^j refers to the change (m^3) of the j^{th} aquifer's exploitation in the i^{th} township. In addition, the positive value refers to the increase in exploitation, whereas the negative value refers to the decrease in exploitation. H_i^j and h_i^j refer to the model's calculated and observed average groundwater level (m) respectively, and the "μ_i" refers to the phreatic aquifer's specific yield. S_i^j means the confined aquifer's specific storage (m^{-1}, j=2,…,6), and M_i^j indicates the aquifer's average thickness (m, j=2,…,6). The A_i means the area of the i^{th} township (km^2).

(5) Adjusted exploitation varies country by country and layer by layer, which should be calculated according to formula as follows. The water level and land subsidence will update after uploading the new withdrawal of groundwater:

$$q_i^j = Q_i^j + \Delta Q_i^j \quad (2)$$

In above formula, Q_i^j refers to the exploitation (m^3) of all townships and all aquifers used in the current loop, and q_i^j means the exploitation (m^3) of all townships and all aquifers used in the next loop.

(6) From the error analysis on the difference between calculated and observed groundwater level hydrographs, historical layer compaction, groundwater level contour, and land subsidence contour, the model will be finished when error meets the criteria. Otherwise we will repeat Step (2) to Step (6) until it does.

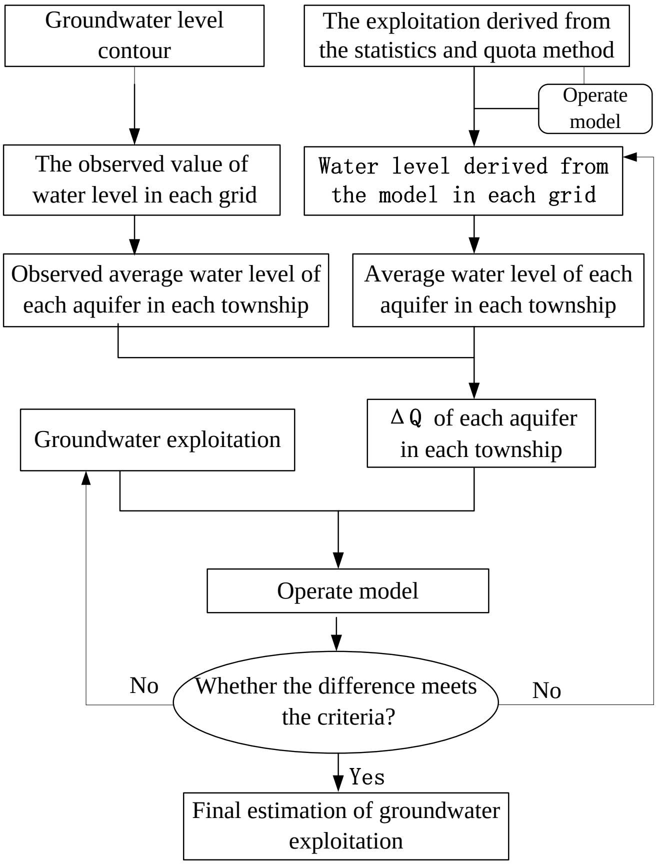

Fig. 1. Flowchart of estimating groundwater exploitation

Result and discussion

Result analysis. The model-based average annual exploitation is estimated to be $8.35\times10^8 m^3/a$, but the average annual exploitation derived from the quota method and statistical data are respectively $9.73\times10^8 m^3/a$ and $5.45\times10^8 m^3/a$. Although foresaid three data are different from one another, their overall fluctuation trends are similar and can mirror the fluctuation of exploitation over past years (see Fig. 2).

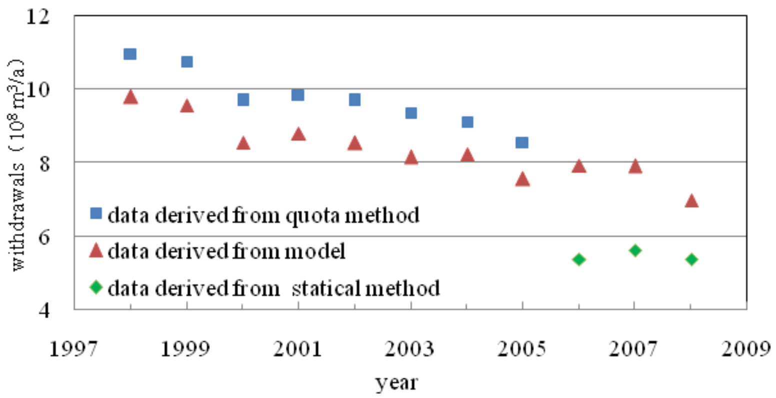

Fig. 2. Comparison chart of groundwater exploitation

From 1998 to 2005, the annual value of groundwater exploitation estimated by a model-based method is 0.87~1.18×$10^8$$m^3$/a smaller than that derived from the quota method, but the estimated value from 2006 to 2008 is 1.60~2.55×$10^8$$m^3$/a greater than the statistical one, with the reason going as follows:

(1) Tianjin has a vast territory and large area, where the agricultural irrigation wells are of great number. However, water pumped for agricultural use depends on demands, the pumping time is uncertain and the pumping intensity is inconsistent, which is bound to inflict the difficulty in summing up the agricultural use of groundwater and ignore some groundwater exploitations. Due to this, the annual value of groundwater exploitation estimated by a model-based method is greater than the statistical one.

(2) As for the annual value of groundwater exploitation derived from the quota method, the groundwater use in same industry but in different years varies from one another. However, the quota method usually refers to a unified quota index, and so there must be difference. From the result we can see that the annual value of groundwater exploitation estimated by a model-based method is slightly smaller than the one derived from the quota method.

(3) As for the model itself, the estimation on the groundwater exploitation is based on the township's average groundwater level. To those townships with small fluctuation of groundwater level, data derived from such a method is identical to the observed value. To those townships with large fluctuation of groundwater level, the estimation is bound to result in difference. However, in the plain area of Tianjin that has a vast scope, fluctuation of the township's water level is not that large, and the error stays within a reasonable scope.

Due to limitation of the data, we fail to allot the groundwater exploitation according to specific location, and so gradual adjustment in the repetitive model calculation is a must. That will cause some difference to the refinement of partial flow field, but exert no influence on the flow field's trend in the entire area. To sum up, method based on model is an efficient way to estimate the groundwater exploitation.

Method discussion. Estimation on the groundwater exploitation by the numerical model is free from the influence by fundamental statistical data like water use quota, and irrigation area etc., and it is an objective value of groundwater exploitation that is based on water balance principle. However, such a method's estimation precision subjects to the precision of the groundwater model. Therefore, establishment of high-precision groundwater model underlies estimation on the exploitation by this method.

High-precision hydrogeological survey, consummate groundwater monitoring data, correct conceptualization of hydrogeological condition and advanced algorithm constitute the precondition for ensuring the establishment of the high-precision groundwater model. In a manner of speaking, the "Coupled groundwater flow and land subsidence modeling" awaits further improvement, in order to facilitate the estimation on the groundwater exploitation as well as to appraise the groundwater resource.

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