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Numerical modeling of regional groundwater flow in the Heihe River Basin, China: Advances and new insights

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Numerical groundwater modeling is an effective tool to guide water resources management and explore complex groundwater-dependent ecosystems in arid regions. In the Heihe River Basin (HRB), China's second largest inland river basin located in arid northwest China, a series of groundwater flow models have been developed for those purposes over the past 20 years. These models have elucidated the characteristics of groundwater flow systems and provided the scientific basis for a more sustainable management of groundwater resources and ecosystem services. The first part of this paper presents an overview of previous groundwater modeling studies and key lessons learned based on seven different groundwater models in the middle and lower HRB at sub-basin scales. The second part reviews the rationale for development of a regional basin-scale groundwater flow model that unifies previous sub-basin models. In addition, this paper discusses the opportunities and challenges in developing a regional groundwater flow model in an arid river basin such as the HRB.

Heihe River Basin, groundwater flow modeling, regional hydrogeology, sustainable groundwater management, ecohydrology

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Semi-arid and arid regions, which are mostly referred to as drylands with annual mean precipitation between 25 and 500 mm, cover about 30% of the global land surface and are inhabited by nearly 400 million people (Williams, 1999). The groundwater resources are vital for semi-arid and arid regions. They support extensive agricultural irrigation, inland population centers, industrial activities, and demand for keeping a healthy ecosystem. In arid river basins, groundwater sustains stream baseflow and moderates water-level fluctuations of water-fed lakes (Hayashi and Rosenberry, 2002). The interactions between groundwater and surface water have a profound effect on aquatic and riparian ecosystems. Moreover, groundwater levels co-determine the environment of soil formation in the long term, including soil texture, moisture regime, and organic-matter content, which successively affects the distributed plant-species composition of vegetation (Klijn and Witte, 1999). Thus, groundwater research is never an isolated part, but a critical component in the eco-hydrological cycle connected with the other related subjects such as meteorology, surface water, ecology and economics.

Numerical groundwater flow models are commonly used as a key tool to understand how the whole groundwater system operates, evaluate the groundwater storage, predict the effects of groundwater irrigation, and guide decisions on water resources management. In arid regions, the real complexity of groundwater systems and flow processes is not easily estimated, and the distributed properties of aquifers

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*Corresponding author (email: czheng@pku.edu.cn) may vary by several orders of magnitude in spatial scale and are often poorly known due to data limitations. Continuously updated numerical groundwater models provide us more realistic and accurate results with larger scale and higher resolution. Furthermore, groundwater models are increasingly being integrated with other models of land surface, climate change, precipitation-runoff, ecological process, and stream routing in recent years (Maxwell and Miller, 2005; Niswonger et al., 2008; Monteiro et al., 2007). All of these modeling efforts increase our understanding of groundwater systems, flow processes, and interaction with other water cycle components.

The arid northwest regions account for one-third of the total land area of China and approximately 4% of the resident population. Groundwater is an essential resource for meeting the water needs of agriculture and industry, and maintaining fragile ecological systems, especially those impacted by frequent droughts (Cui and Shao, 2005). Two of the largest and best-known inland river basins in China's arid and semi-arid regions are the Tarim River Bain and the Heihe River Basin (HRB). The multi-scale landscape, the complex processes of groundwater-surface water interactions, and challenging water management issues related to economics and policy in inland river basins have attracted the attention of hydrologists, ecologists, and economists in recent years. A large number of groundwater models with different purposes have been developed over the past 20 years (i.e., Su, 2005; Wu et al., 2003; Jia et al., 2006, 2009; Liu et al., 2007; Xi et al., 2010; Zhou et al., 2011). With the development of observational networks and the digital databases, the groundwater is gradually treated as an integrated component of the eco-hydrological cycle, rather than an isolated part, and groundwater models are increasing in their spatial scales, from local (sub-basin) to regional with higher model resolution. Reviewing the developmental history of these groundwater models will provide us valuable lessons on and insights into how to improve the conceptualization of the complex groundwater flow characteristics, and understand the patterns and dynamics of groundwater level and storage changes.

The HRB is a representative inland river basin in China (Cheng et al., 2014). The landscape covers the alpine plain in the upstream mountainous region, the oasis plain in the midstream alluvial fans, and the desert region in the downstream plain. The ecological environment in midstream and downstream plains depends greatly on the groundwater and affected by both natural processes and human activities. Since the 1980s, numerical groundwater models have been developed in sub-basin scales to quantify the water resource storage, guide utilization, and predict the groundwater change and ecological effects in the middle and lower HRB. This paper is intended to review the previous groundwater modeling efforts and assess how these models have led to new understanding of and insights into groundwater system characteristics and groundwater resources management. It also discusses the development of a new basin-scale flow model to unify the existing conceptual framework and hydrogeological data.

1 Site description

The HRB, as defined in Figure 1, includes the upstream headwater region of the Qilian Mountains in Qinghai Province, the midstream region of oases and irrigated agriculture in Gansu Province, and the downstream region of Gobi desert in Inner Mongolia. It covers an area of 128610 and 271000 km^2 according to the boundaries delineated in 1995 and 2010, respectively, by West Data Center (West D C) of the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences (West D C, 2011a). The definition of the 1995 boundary took a full consideration of the water resources utilization on the administrative division, whereas the 2010 boundary was defined on the basis of GIS-hydrological analysis of the digital elevation model. There are 41 perennial tributaries in the HRB (West D C, 2011b) and they all originate from the Qilian Mountains. There are 17 major tributaries among them, each with a catchment area of more than 100 km^2. The total runoff volume of these tributaries is 34.43×10^8 m^3 per year. The Heihe River, the river the HRB is named after, is the largest perennial river with a total length of 812 km and a runoff volume of 15.8 $\times 10^8$ m^3 per year, which accounts for about half of the total runoff of all the rivers in the basin. HRB has an arid continental monsoon climate. According to the meteorological data from West D C, the annual precipitation is over 300 mm in the upstream mountainous region, 80–130 mm in the midstream oasis region, and 40–50 mm in the downstream desert region. The annual evaporation is about 800–1000, 2000–2200 and 2300–3800 mm in the monitoring station of upper, middle, and lower HRB, respectively.

The geology of the regional groundwater flow system in the HRB mainly consists mainly of the Quaternary unconsolidated weathered and lacustrine deposits. The regional groundwater flow system is divided into the midstream and the downstream sub-systems by the low-lying mountains along the Hexi corridor and the Badain Jaran Desert. The utilization of water resources centers in the heavily irrigated area of the middle oases and part of lower desert plain. The total water consumption is about 31.47×10^8 m^3 per year, in which 82.6% is consumed in the middle oases (approximately 25.98×10^8 m^3 per year), and 16.1% is consumed in the lower desert plain. In total there are about 8000 pumping wells throughout the entire HRB, and the exploitation volume from groundwater is estimated to be about 7×10^8 m^3 per year.

The main source of water consumption is the ecological water requirement to maintain growth of vegetation and avoid desertification in the lower desert plain of the HRB.

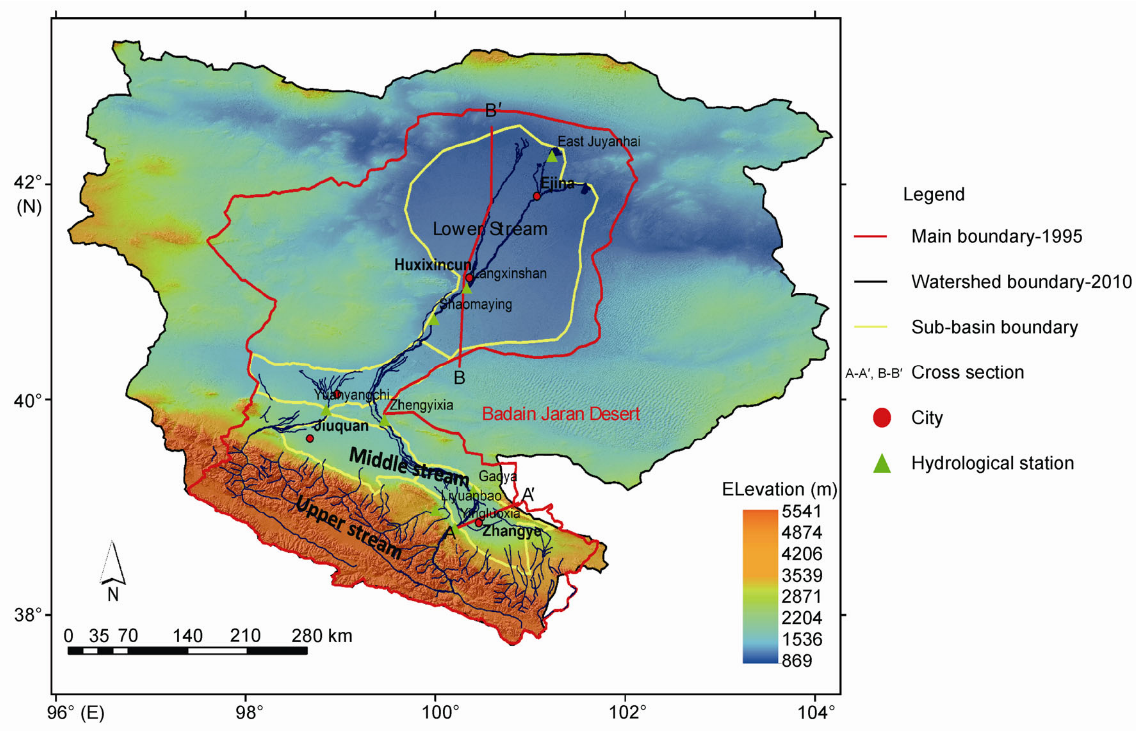


Figure 1 Location and elevation of the Heihe River Basin.

The main plant species of the desert plain in the lower stream region includes *Populous euphratica* and *Tamarix ramosissima* in the riparian forest ecosystem, *Haloxylon ammodendron* in the artificial shrubberies, and *Reaumuria soongorica* in the Gobi ecosystem. These plants take the water from soil and groundwater at depths of 40–200 cm. The survival and the growth of these plants mainly depend on the water content in the soil and groundwater level. According to the groundwater level data accumulated over 12 years, however, the groundwater level varied between 2.18–3.11 m per year, and showed a regional downward trend with lowered 1 m on an average in the lower HRB (Wang and Cheng, 1999; Zhao et al., 2007; Yu and Wang, 2012; Yin et al., 2012).

2 Overview of previous groundwater modeling studies

A total of seven previously developed groundwater models are reviewed in this section, four in the middle HRB and three in the lower HRB. The spatial extents of these models are shown in Figure 2. Table 1 lists the model domain area, spatial dimensionality, and choice of the numerical method. All models are based on either finite difference (FD) or finite element (FE), two major classes of numerical methods used for groundwater modeling. The finite-difference method typically uses a rectangular grid (FD-R) for spatial discretization, but to add more flexibility it can also use an irregular polygon grid (FD-I).

2.1 Groundwater modeling in the middle Heihe River Basin

In the middle HRB, the dynamic interaction between surface water and groundwater, and the exploitation of groundwater are of major concerns. Four groundwater modeling studies have been conducted for the middle HRB at sub-basin scale. The purposes of these models are related mostly to these two issues.

Zhou et al. (1990) developed a two-dimensional groundwater flow model in Zhangye city of the middle HRB (referred to as "Zhou-M" in the subsequent discussion) to assess groundwater storage volume and exploitation available. Zhou-M considered the middle HRB to be an individual sub-basin surrounded by mountainous area which got inflow flux recharge from the Qilian Mountains in the north, and the other boundaries were no-flow boundary conditions. The key feature of Zhou-M is its consideration of both the local hydrological cycle and ecological need of maintaining certain stream flow to the lower HRB. The model results provided the allowable exploitation based on the dynamic water budget, with and without considering the guaranteed stream flow to protect the downstream ecosystem, respectively. Zhou-M illustrated the dynamic exchanges between surface water and groundwater. It showed the total recharge to the groundwater flow system would increase when groundwater pumping was increased. As the

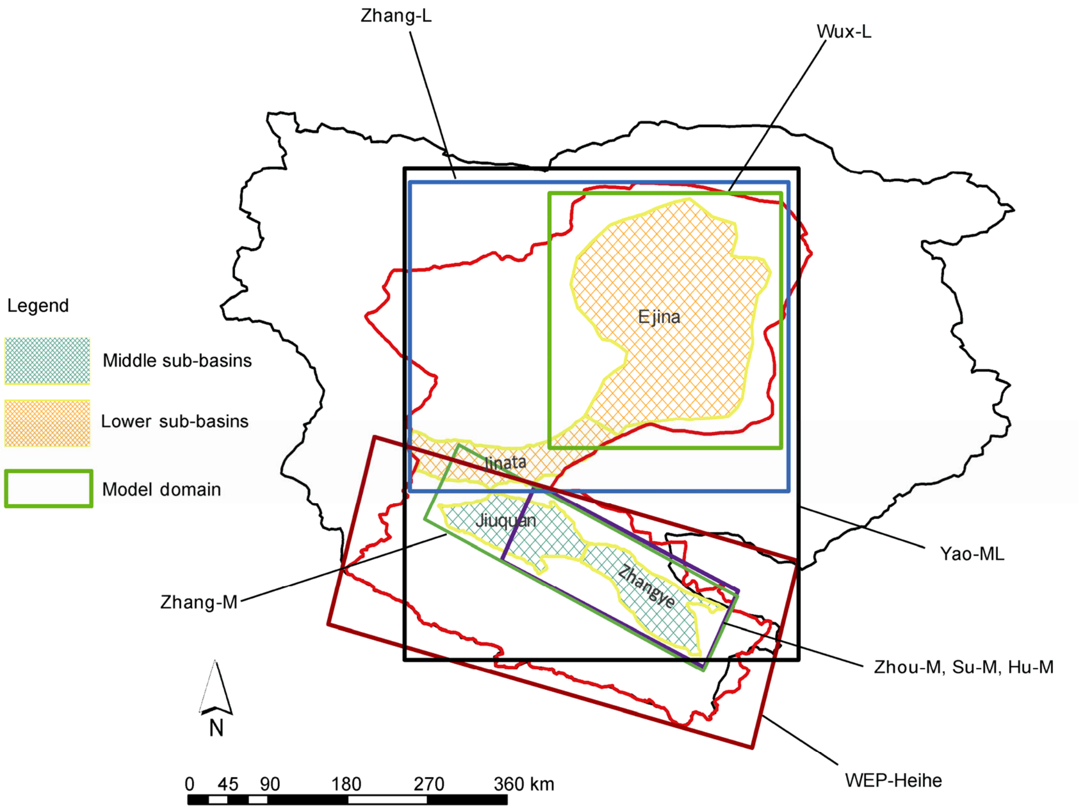


Figure 2 Groundwater model domain within the Heihe River Basin.

Table 1 List of model domain, conceptual type and numerical method of the previous models[a)]

Model	Model domain area (km^2)	Model period		Model layer	Numerical method		
		Simulate	Predict		FD-R	FD-I	FE
Zhou-M	11000	1/1987–12/1989	No	1		√	
Su-M	8146	1/1990–12/1999	1/2000–12/2050	5			√
Hu-M	8716	12/1995–1/2000	1/2000–12/2002	8		√	
Zhang-M	11300	9/1987–8/1988	9/1999–9/2009	2			√
WEP-Heihe	36728	1/1981–12/2002	No	2	√		
Wux-L	33987	1/1996–12/1999	1/2000–12/2005	5		√	
Zhang-L	32900	9/1987–8/1988	9/1999–9/2009	2			√

a) Grid/element is the number of model grid or element in one layer. FD-R: finite-difference method with rectangular grid; FD-I: Finite-difference method with irregular polygon grid; FE: finite-element method

stream leakage to groundwater increased, the evaporation would decrease and the spring volume would decrease owing to the groundwater level decline. The limitation of Zhang-M is its consideration of the entire aquifer as a confined aquifer without an adequate representation of important flow processes. Also, the exchange flux (leakage and upwelling) between surface water and groundwater was specified as fixed recharge and discharge terms, which is estimated by the field flow gaging data. The hydrodynamic processes which stream level and flow response to groundwater level change fail to represent in this model.

Zhang (2005) built a quasi-three dimensional integrated surface-groundwater flow model for the middle and lower HRB, respectively (referred to as “Zhang-M” and “Zhang-L” throughout the rest of the discussion). A distinctive feature of Zhang-M is its integration of the stream flow with the groundwater system. Thus this model simultaneously computed the river leakage with the variable hydrodynamic conditions and the vertical flow between shallow aquifer and deep aquifer during the period of 1987–1988. The groundwater level changes in the middle HRB were predicted during 1999–2009 under two exploitation scenarios: keeping the original exploitation scheme and doubling the original scheme in both confined and unconfined aquifers. The groundwater level displayed a declining trend in both scenarios, but there was no obvious difference between the two scenarios from the computed groundwater level distribution. In the Zhang-M report, there is the lack of detailed analysis about the dynamic exchange flux of surface water and groundwater that was supposed to be important to the results of the model.

Su (2005) built a three-dimensional model (from this point on referred to as "Su-M") by FEFLOW (finite element subsurface flow system) software in the middle HRB. Su-M evaluated the groundwater storage in the middle oases and predicted the water resource demands from 1999 to 2050. Suggestions about reasonable groundwater exploitation were made based on the simulated results. The reasonable allowable exploiting area in the middle HRB was given by Su-M, which mostly consisted of the irrigated area with a high groundwater level and salinization. Though Su-M is a three-dimensional model, representation of physical flow process and flow paths is relatively simple. The flow process and dynamic interaction of stream and groundwater is similar to Zhou-M in that the stream leakage and groundwater discharge are specified as fixed recharge and discharge terms. Thus the outcome of Su-M is highly dictated by the input data, which are the results of a calculated water balance from measured and estimated data. The dynamic interaction between stream and groundwater is once again not represented in the model, lacking the physical process analysis. Moreover, the simulation and calibration period of Su-M is only 10 years but the prediction period is 50 years. There is a need for more discussion about the uncertainty of the model to obtain reasonable predictions.

Hu et al. (2007) established a three-dimensional groundwater flow model (referred to from here on as "Hu-M"), which simulated the groundwater flow in the multi-layered aquifer system, and quantified the interactions among river, spring, and groundwater during the period of 1995–2000. It also predicted the stream leakage flux in the reaches between the Heihe Bridge and Zhengyixia Gorge (a segment of 180 km) for 2002. This model in particular was calibrated not only using historical water levels, but also the investigated baseflow and spring flux. The simulated flow results revealed that the stream loses its connection with groundwater at a reach of the Heihe River, about 80 km from Heihe Bridge. The results also showed a decline of groundwater levels would lead to a decrease in baseflow to river and spring discharge. Hu-M represented the three-dimensional flow process of the groundwater system and dynamic interaction between stream and groundwater. Unlike Zhou-M and Su-M, Hu-M used the stream and spring flux to obtain a better calibration. Furthermore, the water movement in the unsaturated soil layer was considered in Hu-M, which is one of the key difficulties when modeling an arid region.

Jia et al. (2006, 2009) developed a distributed hydrological model (referred to as "WEP-Heihe" here after) for the upper and middle HRB from 1981–2002. The physical mechanisms of the hydrological cycle and the human-induced system of water utilization were both considered to forecast the evolution of water resources in the river basin under a changing climate. The simulation in the WEP-Heihe model consisted of the hydrological cycle and the energy cycle, and groundwater was considered as a subsurface reservoir. WEP-Heihe forecasted the monthly stream flow, the flow in dry and flood seasons, and the discharges of small rivers out of Qilian Mountains. This model also estimated the lateral inflow flux to groundwater from the mountain front to be about 0.23×10^8 m^3 per year. The possible changes of the water budgets in the middle HRB were evaluated when the underlying conditions were changed. The predicted results showed that water conservation in the forests would make the runoff from mountains slightly decrease, but the storage of soil water and groundwater would increase. The effective measurement of increasing the river flow and decreasing the deficit of groundwater storage caused by over exploitation in the middle HRB would be to change the cultivated farmland into grassland. As a hydrological model, WEP-Heihe was capable of simulating the water flow processes of land surface-like evaporation, interception, and runoff, but its treatment of the groundwater component was too simplistic to represent the groundwater flow characteristics in the middle HRB.

2.2 Groundwater modeling in the lower Heihe River Basin

In the lower HRB, groundwater dependent ecosystems comprise a complex and fragile desert plain. Since the annual precipitation is only 40–50 mm, the main source of groundwater recharge is the Heihe River. The rational allocation of water resources from the middle basin to the lower desert region to maintain a healthy ecosystem is a fundamental issue. Therefore, modeling studies are concerned with changes in the groundwater level in the lower HRB under different water allocation schemes, which will affect how much stream flow discharges to the lower plain.

Wu et al. (2003) developed a three-dimensional groundwater flow model (subsequently referred to as "Wux-L") which contained saturated and unsaturated zones in the Ejina Basin of the lower HRB based on a relatively comprehensive characterization of the groundwater flow system. Wux-L predicted the change of groundwater level during 2000–2005 in the lower HRB when surface water was delivered under four different scenarios. The optimal scenarios of surface water diversion from the middle to lower HRB was calculated to be in the range of 7.5×10^8 m^3 per year. It is noteworthy that Wux-L provided a systematic characterization of the structure of the hydrological setting, the characteristics of the flow system, boundary conditions, and the vegetation distribution using a substantial amount of data from the lower HRB for development of the numerical model. These data provided the foundation for subsequent modeling studies in this region.

Zhang-L simulated the groundwater flow system in the lower HRB during the period of 1987–1988, and was used to predict the dynamics of groundwater level change of over 10 years from 1999 to 2009. The results showed that the reasonable discharge from middle to lower HRB was 7.0×10^8 m^3 per year. Similar to the Zhang-M, Zhang-L cannot provide a detailed analysis of computed stream leakage to groundwater.

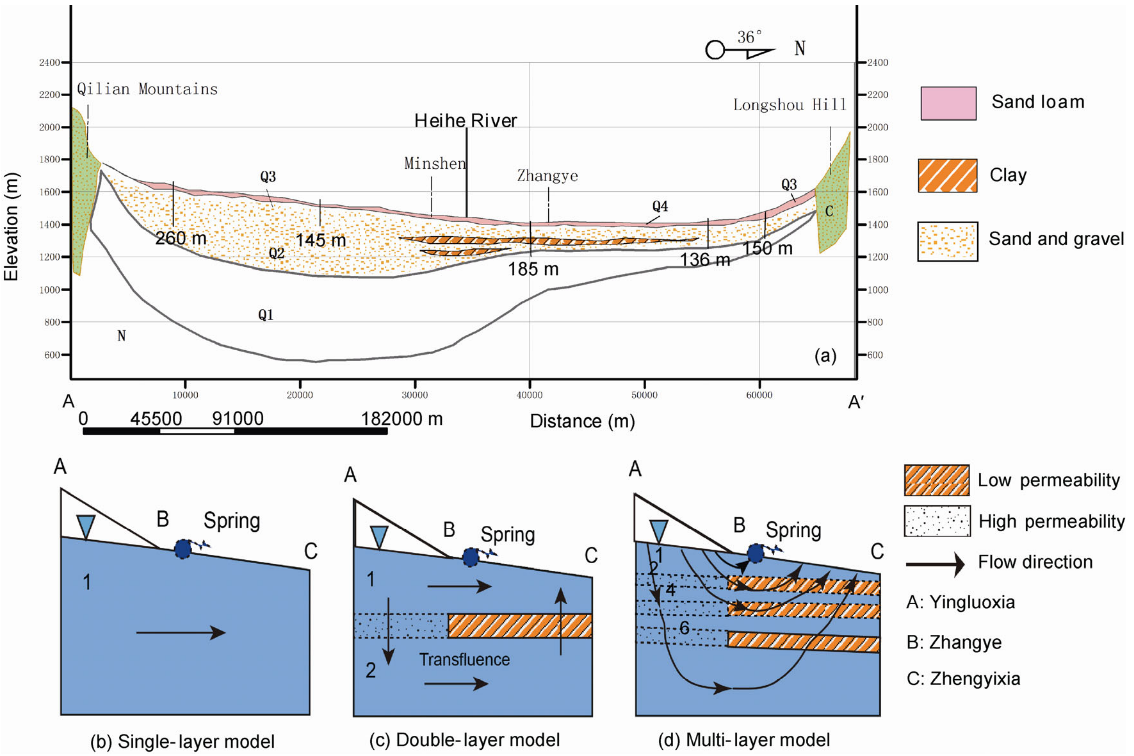
2.3 Conceptual models and numerical approaches

Wang et al. (2009) classified the numerical groundwater models of the HRB into three categories according to the structure of conceptual models: single-layer model (2D), double-layer model (quasi-3D) and multi-layer model (3D). Figures 3 and 4 illustrate the cross-sections of the middle and lower basins and their conceptual types, respectively, whose locations are marked as lines A-A′ and B-B′ in Figure 1. A simplified 2D model like Zhou-M can simulate the groundwater level distribution from basin scale to regional scale, but fails to represent the three dimensional flow characteristics in the middle basin, in which the flow is downward from A to B and upward from B to C (Figure 3 (b)). Thus it is difficult to consider the vertical interaction between stream and aquifer. Quasi-3D models like Zhang-M and Zhang-L (Figures 3(c) and 4(b)) are the double-layer models, which include unconfined and confined aquifers. Flux exchange between the two aquifers was calculated by the leakage coefficient in different parameter zonations. The hydrological model WEP-Heihe was also a quasi-3D model in which the groundwater system was considered a reservoir containing a shallow part and a deep part, and the river leakage, and the infiltration from the unsaturated zone, was regarded as the recharge. Quasi-3D models do not only represent three dimensional flow pattern of the groundwater system, but they are also easily integrated into other hydrological components as well, such as surface water, atmospheric boundary, and the crop growth process (Krysanova et al., 2005).

Su-M, Hu-M, and Wux-L are all 3D models (Figures 3(d) and 4(c)), which respectively include 5, 8, and 5 model layers. 3D models can fully delineate the groundwater system from recharge area to discharge area; however, they require sufficient 3D data that contain 2D distributed property and vertically stratified information. Though some models have multiple layers like Su-M, the results cannot represent 3D characteristics for the recharge and discharge. For example, the specific information of well depth and screen position is needed for each pumping well.

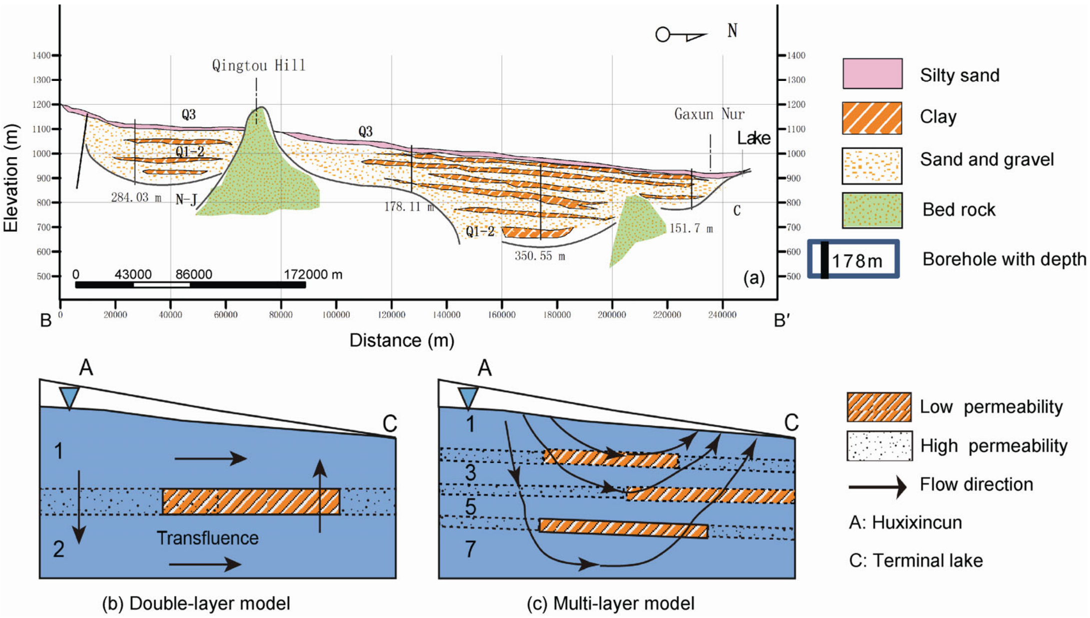
2.4 Recharge and discharge processes

Recharge, as a fundamental component of groundwater systems, is either measured and specified or estimated during model calibration. Choosing an appropriate approach to represent recharge in a groundwater model depends on both hydrological factors and study objectives (Sanford, 2002). In the middle HRB, the infiltration of precipitation and irri-



(b) Single-layer model (c) Double-layer model (d) Multi-layer model

Figure 3 Cross-section A-A′ and the conceptual models (Wang and Zhou, 2009) of the middle HRB.



(b) Double-layer model

(c) Multi-layer model

Figure 4 Cross-section B-B′ and the conceptual models of the lower HRB.

gation water from stream or pumping is considered an important recharge term linking the atmospheric boundary to the groundwater system but variably controlled by climate, geological framework, and human activities in the oases. In some simple groundwater models, the amount of recharge to groundwater from precipitation and irrigation return is simplified by the product of the sum of precipitation and irrigation and an infiltration coefficient that is estimated based on the field experiments. The Zhou-M model used this method, which defined the infiltration coefficient as a parameter to specify in the different recharge zones and irrigated areas of the first model layer. However, this method neglects the physical factors that influence the recharge rate and flow process in the unsaturated zone, which directly connects groundwater to the atmosphere. Scanlon et al. (1997) pointed out that the water movement in the unsaturated zone was restricted mostly in arid regions. In the HRB, the aquifer thickness and the depth to water table vary from the piedmont alluvial plain to the alluvial fan. The dry soil usually retains the recharge from precipitation before infiltrating water reaches the water table. Therefore, the flow process in the unsaturated zone cannot be ignored in groundwater models. Tian et al. (2012) developed a coupled approach based on a land surface model (SiB2) and a 3-D variably saturated groundwater model, thus the infiltration and ET in the vadose zone were simulated by SiB2 and then applied as input data to drive the groundwater flow model.

In the Hu-M model, the weight function method (Chen, 1998) was used to depict the hysteresis effect of precipitation infiltration into the unsaturated zone. Then the delayed recharge from leakage of stream and infiltration were investigated by Wang et al. (2010). It demonstrated that the delayed recharge for leakage from Heihe River was about 4–8 days but the delayed recharge for farmlands infiltration will be at least one month. The WEP-Heihe model added a transitional layer between surface water and shallow groundwater layer to reflect the hysteresis effect of precipitation infiltration in the thick unsaturated zone. The Wux-L model added a simple moisture transfer model in the unsaturated zone, which calculated the negative pressure based on the soil moisture characteristic curve. Automated inverse techniques, combined with measured base-flow or groundwater age, are often used as an effective method to estimate the recharge rate, but they have not been used in previous models in the HRB.

Evapotranspiration (ET) is used to represent the evaporation of groundwater near the land surface in an unconfined aquifer and the direct transpiration of groundwater by plants. Low precipitation and high ET is a distinct characteristic in arid regions. ET, an important discharge term in groundwater models, is almost 100 times greater than precipitation in some areas of the lower HRB (Wu et al., 2003). Zhang-M used the relation between the water table depth and the ET rate to estimate the ET in the middle HRB, which was based on lysimeter data:

$$q_e = 1157.24H - 250.83, \quad 0.25 \leqslant H \leqslant 0.5, \tag{1a}$$

$$q_e = 334.05 - 143.89H + 14.81H^2, \quad 0.5 \leqslant H \leqslant 6.5, \tag{1b}$$

where q_e is the ET rate (mm/year), H is the depth to water table. According to the depth to water table in the distributed discharge area, either eq. (1a) or (1b) was chosen to compute the ET rate. The extinction depth of ET in the middle HRB was set to 6.5 m, which means ET does not remove any groundwater below the water table depth of 6.5 m. Similarly, Zhang-L used the relation below to estimate the ET rate with an extinction depth of 5 m in the lower HRB.

$$q_e = 728.11 - 372.65H + 46.81H^2, \quad H \leqslant 5 \tag{2}$$

The Su-M model only considered groundwater evaporation without transpiration and directly specified the ET rate under different water table depths, with the extinction depth being 10 m in the middle HRB. Hu-M estimated the total ET amount (Q_{ei}) based on an evaporation coefficient at surface water (ε_0), water table depth (D_g), the area of discharge zone (A_i), and an empirical coefficient (b) which was set to 0.9858 in the model.

$$Q_{ei} = A_i \cdot \varepsilon_0 \cdot \mathrm{e}^{(-b \cdot D_g)}. \tag{3}$$

ET is a dynamic variable that is related to the solar radiation, landscape, and especially the plant growth. The semi-empirical method based on observed data fitting mentioned above is more suitable for small scale, e.g., site or plot scale modeling that has the relatively unique land cover. Regional scale modeling should make full use of remote sensing products to classify the land cover and calculate the corresponding extinction depth.

The Wux-L model considered plant growth using the interpreted vegetation classification and ET rate from remote sensing data. It was important to consider ecological factors in a groundwater model in the lower HRB because of the essential role played by groundwater for vegetation growth. The model domain was separated into two categories, bare land and vegetated land. In vegetated land, two periods, the growth period and the dormant period, were considered. During the dormant period both on bare land and vegetated land, the ET rate was directly specified according to different water table depths with an extinction depth of 4 m. During the growth period on vegetated land, the total amount of groundwater evaporation and plant transpiration was statistically computed through the ET of individual plants and the distributed area of vegetation classification.

The interaction between surface water and groundwater is a major concern in the middle HRB, which mainly includes river leakage and spring discharge. In the Zhou-M and Su-M models, the river leakage in the piedmont alluvial plain was specified as linear source recharge, and in the edge of the alluvial fan was specified as the constant head boundary. In the Hu-M model, the process of stream discharge to groundwater was represented by infiltration and injection (Figure 5). The former was used under the condition that the water table was below the bottom of the semi-permeable streambed, and unsaturated flow was involved; the latter was used when the water table was close to river bed and no unsaturated flow developed beneath the river. This method provides good conceptualization, especially for the stream leaving the mountain front in arid regions.

In the middle HRB, the total amount of spring discharge from the groundwater to stream is as much as 10×10^8 m^3 per year (Ding et al., 2006). In the Zhou-M model, the spring was treated as a constant head boundary, and then the spring flow flux was calculated from surrounding areas. This method was used to forecast the variation in spring flow, groundwater level, and discharge from the Zhengyixia Gorge under the influence of hydraulic engineering projects. In the Zhang-M model, the spring area was regarded as the discharge area, and the discharge flux was calculated using a proportionality coefficient of the spring water level and the groundwater level. The Su-M model directly used the measured spring flux as the discharge flux. In the Hu-M model, the spring was also treated as the constant head boundary and was considered using an equivalent hydraulic conductivity (Chen and Jiao, 1999) to replace the hydraulic conductivity when the seepage velocity of the spring was very large and groundwater flow did not follow Darcy's flow.

Groundwater exploitation and return flow from irrigation are complicated in the middle HRB. Difficulties exist not only in the rationalization of numerical methods being ap-

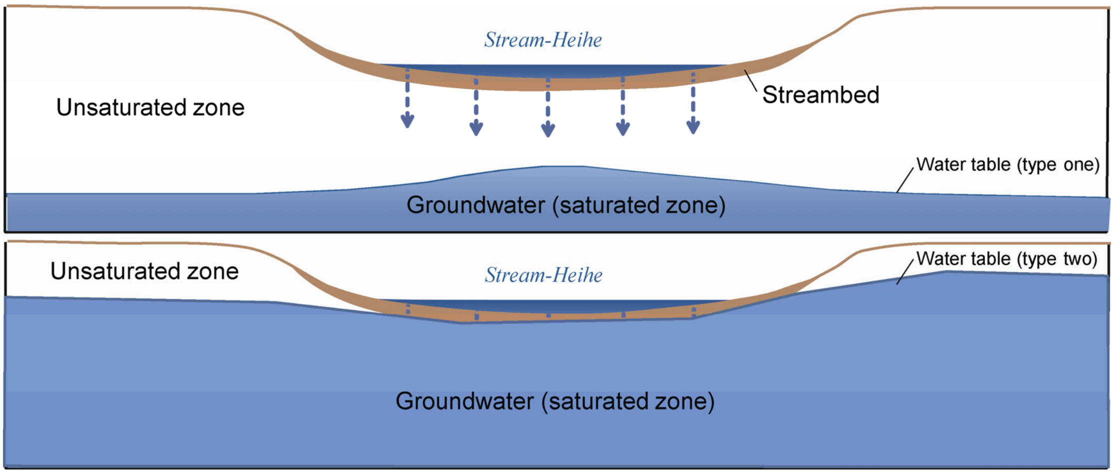


Figure 5 Conceptualization of a stream discharge to groundwater.

plied in the reality, but also in the collection of information. Based on the available data from WestDC, there are about 6700 pumping wells in the middle HRB. Over 4000 wells are concentrated in the irrigation areas along the stream corridor, but the effects of groundwater irrigation on stream flow have never been studied. Moreover, pumping data with long time series are lacking, and the vertical information such as well depth and the screen position is missing. The Zhou-M model was a single layer model, so the groundwater exploitation was specified as the areal discharge. The Hu-M model allocated the total pumping to multiple model layers according to the depth of pumping wells. Other models did not describe this part in their published materials.

2.5 Summary of previous models

Hill et al. (2013) pointed out that the knowledge about the hydrogeological system can be used as an important index to evaluate groundwater models. Particularly, 3D models like Hu-M and Su-M in the middle HRB and the Wux-L model in the lower HRB have added knowledge about the hydrological and geological frameworks at basin scale; knowledge about the possible interacting processes among the unsaturated zone, stream, and groundwater; and knowledge about past and future changes in system dynamics and characteristics of the HRB. The limitations of previous models are that they focused mostly on the sub-basin scale, which failed to analyze the action-response relationship between the middle HRB and lower HRB. Some key processes in the middle HRB, such as the interactions between groundwater and surface water and the dynamic relationship between groundwater level and vegetation distribution, were far from sufficient analysis and the physical mechanisms were not clearly understood. Moreover, even though the appropriate ecological flows were estimated from previous models for the lower HRB, some key scientific issues have not been fully addressed; for example, does the ecological state (plant pattern) change in response to the flow release from the middle HRB, how much of the released water is transmitted into the aquifer and how much is consumed by plants, and how does the groundwater fluctuate along the transverse section of the riparian zone? Nevertheless, these models provide good examples to deal with the specific problems and provide a solid foundation for the development of regional integrated models.

3 Development of an unified basin-scale flow model

3.1 Why does regional groundwater flow model matter in the HRB?

Developing a regional groundwater flow model in the HRB is driven mostly by the needs to (1) understand the flow paths characteristics of groundwater system; (2) define the watershed boundary and estimate trans-boundary flux among sub-basins; (3) guide eco-hydrogeological data collection in regional scale; (4) access the groundwater storage and the water budget; (5) define the distributed discharge and recharge considering the effect of human activities, and (6) make predictions for water resources management in the future (Belcher et al., 2010; Pool et al., 2011; Cao et al., 2013). In the HRB, the relation between water resources utilization and the ecological requirement is dependent on the basin-wide system dynamics and system behaviors. Thus it is essential to develop a regional groundwater model covering the middle and lower plains. Furthermore, competing views still exist for the conceptualization of certain areas such as the Hexi Corridor low-lying mountains and the Badain Jaran Desert. The recharge sources of the Badain Jaran Desert have great discrepancies (Chen et al., 2004; Gates et al., 2008). Because of the above reasons, Yao et al. (2014) developed a basin-scale groundwater model in the HRB (referred to as “Yao-ML” in the following discussion), in which the midstream oases and downstream desert plain were considered the entire model domain. As a basin-scale groundwater model of HRB, the Yao-ML model assessed the global water budget that includes the lateral boundary flux from Qilian Mountains to the middle and lower HRB, and evaluated the plausibility of inter-basin flow in the Hexi Corridor low-lying mountains using particle tracking.

3.2 Hydrogeological framework—Data model

A large number of spatial and temporal data in multiple scales and sources are needed to represent the hydrogeological system and develop a regional model. All the available data like borehole, well, river, pumpage, and hydrogeological interpretations from environmental tracers must be organized in a geographic information system (GIS). A hydrogeological framework is essentially a spatially distributed geodatabase describing the conceptual model for a specific study site. It usually includes geological setting, aquifer extent and thickness, top and bottom elevations of aquifer/aquitard, hydraulic properties, and boundary conditions under a defined hydrogeological unit (Kahle and Bartolino, 2007). The hydrological framework contains a large number of geospatial data in different scales, resolutions, and data formats. Thus a key step is defining the unified parameterized representation and building the data relations and the criteria of transformation. For example, a key parameter of the ET process, the distributed extinction depth, is calculated and transformed through land cover and then stored as a feature class in the data model. The hydraulic conductivity is related to the hydrostratigraphy constructed from boreholes. Environmental tracer analysis can yield valuable information about the flow path as the auxiliary information to help constrain the numerical model. Also, as the groundwater lies hidden beneath the land surface, it is less visible and less readily mapped compared to surface water. Thus, development of a hydrogeological framework requires approaches specifically designed for groundwater to describe the extent and thickness of an aquifer, 2D GIS maps, and vertical stratigraphic information from boreholes or wells.

In HRB, the major difficulties to developing a regional hydrogeological framework are how to represent the variable landscape, complex geological structure, and multiple physical processes. Yao-ML first built a geographic data model using the software tool "Arc Hydro Groundwater", which was designed specifically for groundwater systems. This data model focuses on classes of groundwater information in a unified geodatabase and representation of the invisible subsurface containing the geological structure and the aquifer distribution (Strassberg et al., 2007). Various categories of geospatial groundwater data in the middle and the lower HRB were compiled by this unified data model. Since the HRB covers three provinces from upstream to downstream, previous geological surveys were carried out according to administrative districts delineated by the Mining Bureau of Gansu Provinces in the 1990s. The geological settings and data were published in some reports dispersedly, so this unified geodatabase provided the foundation for the basin-wide groundwater research. Figure 6 shows the contents of the hydrogeological data model. In the Yao-ML model, the groundwater model was conceptualized as consisting of five model layers, including one unconfined aquifer, two confined aquifers, and two aquitards. Variable landscapes like mountainous terrains and fluvial valleys and special geological structures such as inferred faults were represented as parameter feature classes. The "virtual model layer" is used to represent the hydrogeological unit that is absent, in which the hydraulic properties are identical to those of the unit underneath it.

3.3 Transient flow model and model calibration

Figure 6 shows the framework for developing a 3D transient numerical groundwater flow model after completing a hydrogeological data model, based on the workflow of the regional groundwater flow model structure in Death Valley (Belcher et al., 2010). First, the hydrogeological framework is the basis of the numerical model. Second, the work of developing a transient numerical model mainly includes two parts: Model construction and model calibration. Model construction requires determining the spatial and temporal discretization, discharge and recharge, boundary conditions, hydrogeological properties, and groundwater pumpage. It is also important to consider the time points of key events occurring in the HRB, such as the policy of water release from the middle to lower HRB taking effect in 2002.

Figure 7 shows the regional groundwater model grid with 1km resolution in the HRB (Yao et al., 2014). Model calibration includes designing or choosing the suitable approach, selecting observation data type and rethinking the alternate conceptual model. In groundwater models, the hydraulic heads and discharge observations are often used to calibrate the model. Hydrogeochemical, isotopic, and thermal data should be used as supplementary and complementary information to help constrain the calibration of the flow model and to indicate whether overall flow directions

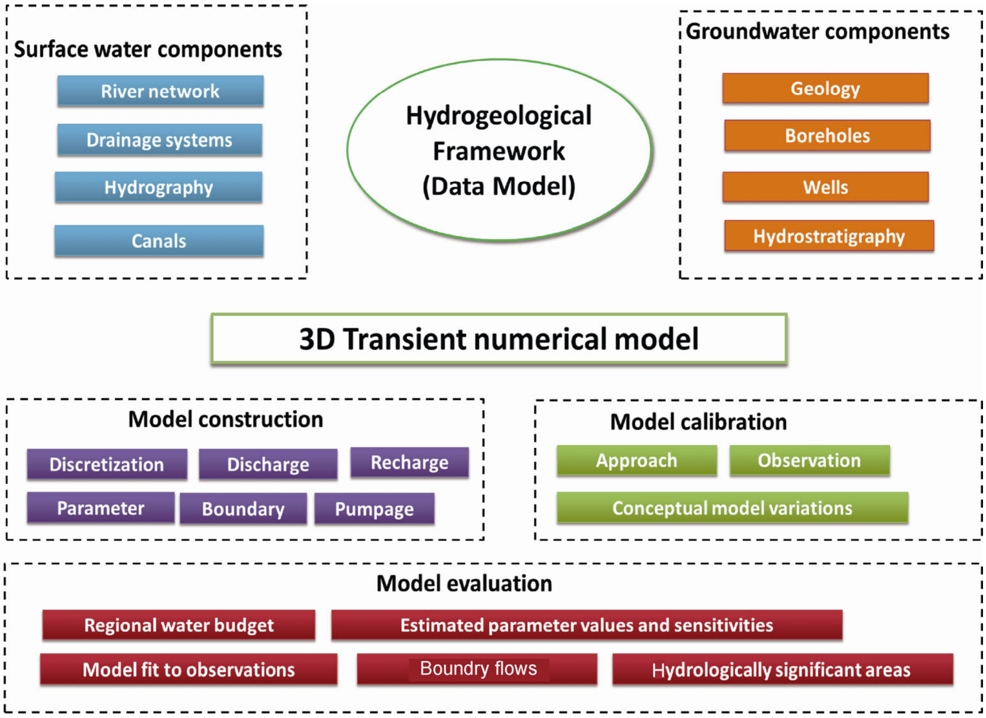


Figure 6 Framework for developing a regional 3D transient groundwater flow model.

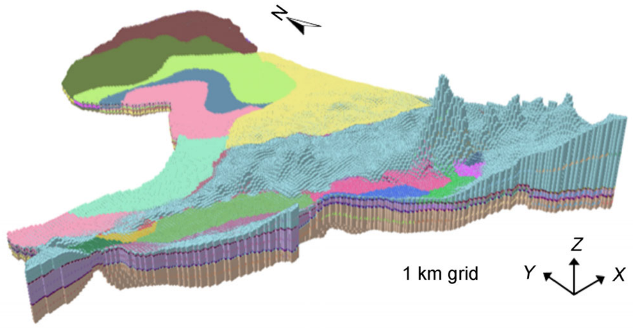


Figure 7 Regional groundwater model grid for the middle and lower HRB with different colors showing different aquifer property zonations. Yao et al. (2014).

and magnitudes are reasonable. It is noteworthy that calibration of a regional model may not be deemed well enough even if the observed hydraulic heads and stream discharges are fitted closely with the calculated values. Capturing the major physical processes and evaluating the uncertainty of calibrated parameters are the effective means to judge the quality of a calibrated model. Thus model calibration should be accompanied by local and global sensitivity analysis as well as uncertainty analysis to assess the robustness and reliability of simulation results (Wu et al., 2014).

The conceptual model is critical for groundwater model development (Gillespie et al., 2012), thus modification of the conceptual model is a necessary step during calibration. The calibration process produces a series of alternate conceptual models. The best fit to water level, discharge or boundary flow observations was calculated for each conceptual model. Other analysis methods are used in conjunction with hydrogeologic data and knowledge to judge whether the conceptual model is plausible. The previous HRB models have not detailed conceptual model calibration. The regional water budget and boundary fluxes are the major concerns that drive us to develop a regional model. Moreover, the total discharge and recharge need to be carefully evaluated based on the simulation results. Finally, special attention should be paid to hydrogeologically significant areas such as mountainous terrain and desert.

4 Opportunities and challenges

4.1 Opportunities

A series of research projects have recently been launched by the National Natural Science Foundation of China (NSFC) to explore integrated ecological and hydrological processes and their linkage with socioeconomics in the HRB. As a critical component and key driver in the ecohydrological processes, groundwater is at the center of field and modeling studies in the HRB. This provides unprecedented opportunities to not only fill in the data gaps in some data scarce areas, but also acquire new insights and new knowledge related to the role of groundwater in the basin-wide hydrological cycle and ecosystem functioning.

For example, analysis of spatial and temporal patterns of green and blue water flows basin-wide (Zang et al., 2012) provided the water consumption footprints for the regional modeling. Spatial variability of the vertical hydraulic conductivity of the streambed in the lower HRB (Min et al., 2013) yielded independent constraints on the range of model parameters. The study of groundwater recharge and hydro-geochemical evolution in the Ejina Basin (Wang et al., 2012) provided more data to support the development of a sound conceptual model with proper flow paths recharge and discharge areas. The hydrogeochemical analysis of isotopic data from the Badain Jaran desert assisted in obtaining regional groundwater flow path information in remote areas of scarce data (Zhao et al., 2012), and the isotopic evidence for the origin and composition of soil moisture and surface runoff in the upper basin provided insights into the water balance in the HRB (Zhao et al., 2011). The estimation of groundwater storage based on the remote sensing data like GRACE (Cao et al., 2012) served as an independent reference for comparison with computed results from numerical models. The new data of and new insights into groundwater dominated processes can greatly contribute to the understanding and modeling of integrated basin-wide ecohydrological processes and complex system behaviors.

4.2 Challenges

Even though a significant amount of research has been carried out and a wealth of monitoring data has been accumulated for the past 30 years in the HRB, the understanding of some complex hydrogeological processes is still limited, especially in those areas of high mountains and remote deserts. Also, some key issues in previous models, such as the handling of the unsaturated zone, representation of irrigation return flows, and interactions between surface water and groundwater in the presence of pumping wells, will become more complicated and more challenging to simulate in regional transient models.

The 3D transient groundwater flow model requires intensive, high-quality datasets, but current groundwater monitoring instruments can hardly meet those requirements. Also, the dynamics of surface water have a great impact on groundwater, but the number and spatial coverage of the monitoring devices to observe the responses in groundwater levels are limited relative to the size of the basin. Thus the data needs will remain a major challenge for basin-scale groundwater modeling and hydrogeological studies. It is noteworthy, however, that the development of observational networks and digital databases for the HRB (Li et al., 2011, 2013) can provide the independent and high-quality datasets that can be used to improve the accuracy and reliability of groundwater simulation and calibration. New technologies such as the fiber optic distributed temperature sensing applied in the middle HRB to investigate the interactions between surface water and groundwater (Huang et al., 2012) make it possible to quantify the characteristics of complex stream-groundwater interactions quickly and cost-effectively.

5 Conclusions

Previous numerical models at sub-basin scales have increased our knowledge and enhanced our understanding about the flow patterns, exploitable resources, and dynamic changes and evolutions in groundwater levels and storages in the middle and lower HRB; however, sub-basin scale models cannot accurately portray the dynamic connection between the middle and lower basins and fail to address questions about the basin-wide system behaviors. With the advances of eco-hydrological research in the HRB, developing regional, basin-scale groundwater models with high spatial and temporal resolutions is an inevitable direction in the HRB and urgently needed for water resources management.

A hydrogeological framework in a unified GIS data model has been developed for the groundwater flow system of the middle and lower HRB. Based on the hydrogeological framework, a 3D transient groundwater flow model for the middle and lower HRB is being constructed and calibrated. The new eco-hydrological research initiative at the HRB offers unprecedented opportunities for the groundwater modeling efforts by providing massive new observation data and new conceptual understanding of physical processes. The basin-wide groundwater model, in turn, constitutes the core element of the integrated ecological and hydrological model of the HRB intended to achieve sustainable management of the water resources and ecosystem health. Although a high-resolution basin-scale groundwater model can be computationally demanding, cloud platforms offer unprecedented cost-effective and flexible computing resources, especially for parameter estimation, sensitivity analysis, and stochastic uncertainty analysis (Hunt et al., 2010; Liu et al., 2013).

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