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RESEARCH ARTICLE

Assessing the impact on groundwater safety of inter-basin water transfer using a coupled modeling approach

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Abstract Surface water and groundwater always behave in a coupled manner and are major components of hydrologic cycle. However, surface water simulation models and groundwater simulation models are run separately most of the time. Few models focus on the impact of hydraulic changes in the surface water flows on the groundwater, or specifically, the impact of a water transfer project to fill a seasonally dry channel. In this study, a linked surface water and groundwater simulation model was developed to assess the impact of a trans-basin water diversion project on the groundwater. A typical plain area east of Beijing was selected as a case study, representing Beijing's main source of groundwater used for drinking water. A surface water quality model of the Chaobai River was developed based on the Water Quality Analysis Simulation Program (WASP), and a groundwater model was developed based on the Modular Finite-Difference Groundwater Flow Model (MODFLOW) and the Modular 3-D transport model (MT3D). The results of the surface water simulation were used as input for the groundwater simulation. Water levels and four contaminants (NH_3-N, COD_{Mn}, F, As) were simulated. With the same initial and boundary conditions, scenario analyses were performed to quantify the impact of different quantities of diversion water on the groundwater environment. The results showed the water quality of the groundwater sources was not significantly affected.

Keywords surface water, groundwater, linked model, groundwater safety impact assessment, water diversion

1 Introduction

Surface water and groundwater are complex environmental systems that behave in a coupled manner. Both systems are major components of the hydrologic cycle. The quantity and quality of the groundwater are closely linked with those of the surface water, thus, alteration or contamination of one commonly affects the other [1–4]. Studies show that continuous excessive pumping of riverside groundwater can lead to extreme surface water shortages [5], and that artificial groundwater recharge reduces the frequency of extreme surface water shortages [6]. The pollutants in contaminated surface water can be transferred into the groundwater and degrade groundwater quality at the groundwater–surface water interface [7,8].

Coupled modeling of the relationship between surface water and groundwater has been used for a few decades [2,7,9–11]. The coupled models have extensively been applied for groundwater assessment, although accuracy and computational efficiency of these models need to be continually improved [12–17]. Most linked models focus on the watershed-scale, combining a watershed model, such as Soil and Water Assessment Tool (SWAT), and a groundwater model [11,18,19]. Few have focused on the impact that hydraulic changes to the surface water has on the groundwater, or specifically, the impact of a trans-basin water diversion project, which fills an ephemeral channel during the natural dry seasons. Because many water diversion projects have been implemented in China in recent years [20,21], the environmental assessment of water transfer projects on groundwater is needed. The objective of this research is to develop a coupled surface water and groundwater model, and to simulate the impact of water transfer projects on groundwater.

2 Data and methods

The study area is the Chaobai River alluvial plain, located in the Shunyi District of Beijing (Fig. 1). This is an area of plains that is typical of northern China. The Chaobai River is ephemeral and seasonally dry at most times. There are several important groundwater sources of drinking water

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along the river. The Chaobai River alluvial plain has a multi-aquifer structure, with the aquifer being thicker in the north and thinner in the south. The northern aquifer's coarse particles generally consist of sand, gravel, and pebbles. The southern aquifer's fine particles generally consist of fine sand and silt [22]. With the abundant groundwater resources and an annual extraction volume exceeding 500×10^6 m^3, the study area is one of the most important groundwater sources in Beijing, and the groundwater is highly sensitive to changes in the environment [23].

Since 1994, the groundwater level has fallen sharply in the study area due to over-pumping and the evaporation of surface water [23]. To alleviate the water shortages in the study area, a trans-basin water diversion project has been proposed. The project would first treat polluted water from the nearby Wenyu River using a membrane bioreactor (MBR), and then divert the treated water to the Chaobai River, as shown in Fig. 1. The possible changes to the groundwater flow field and the local water quality after the introduction of the treated water to Chaobai River were major concerns of the public. As the study area is representative of the Beijing area, and typical of groundwater in an environmentally sensitive plains area, it is necessary to construct a linked surface water and groundwater model, and then evaluate the impact of the project by scenario analysis.

An investigation of the geology, climate, hydrology, water quality, and pollution sources in the study area was conducted. An assessment of the current status of the water environment in the study area was performed, and the major water-environmental problems and main pollutants were identified. In general, the water quantity in the Wenyu River is sufficient, but the water quality is poor, being inferior to grade V of the national environmental standard for surface water (NESSW) (GB3838-2002). The groundwater in the study area is of excellent water quality, and can generally achieve grade II of the national environmental standard for groundwater (NESGW) (GB/T 14848-9), except for the concentration of arsenic (As). The route of water diversion is shown in Fig. 1, and the treated diversion water would achieve grade IV of the NESSW. The national-standard-grade values of the relevant water-quality indicators are listed in Table 1.

To support the scenario analysis, a linked surface water and groundwater model was developed for the study area, and the spatial-temporal distributions of various water quality indicators were simulated in both the surface water and groundwater. In consideration of the quality of both the diversion water and the groundwater in the study area, the permanganate index (COD_{Mn}), ammonia (NH_3-N), arsenic (As), and fluoride (F) were selected as the water quality indicators to be simulated. After a comprehensive analysis of the major water-environmental problems that could be caused by the trans-basin water diversion project, three scenarios were devised and then analyzed. The technical

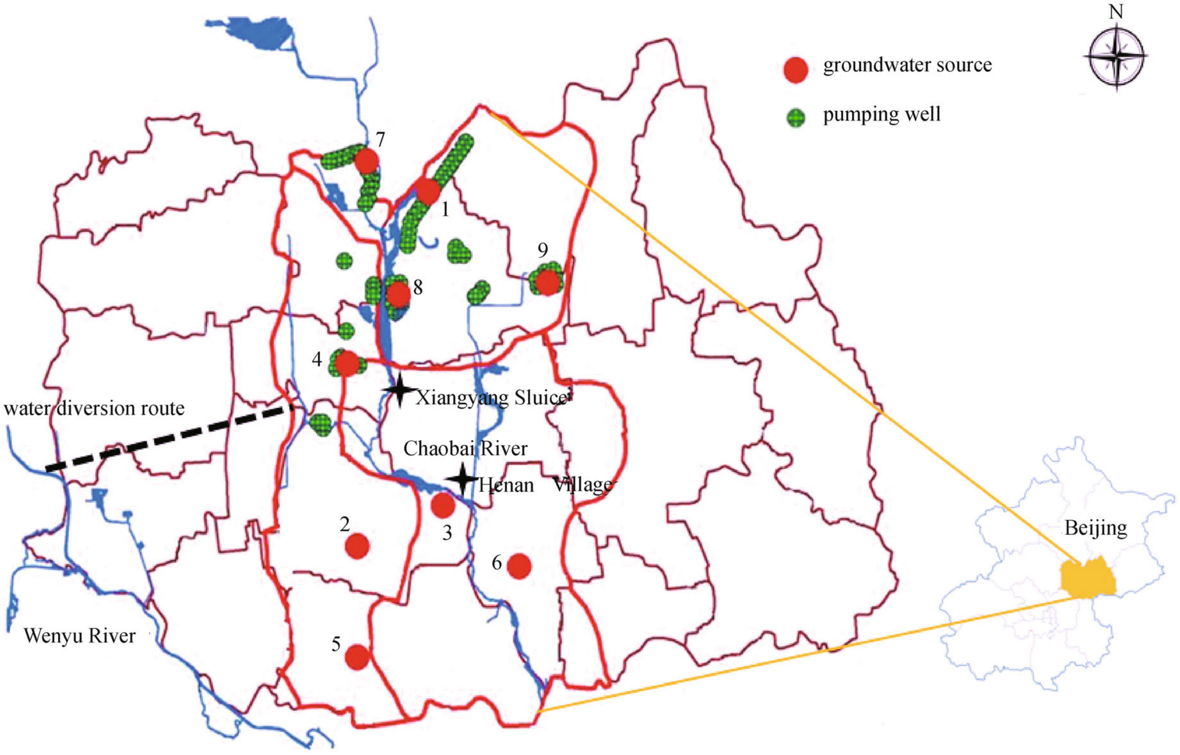


Fig. 1 Study area in the Shunyi District, Beijing

Table 1 Standards for selected contaminant from the NESSW and the NESGW

standard grade		As/(mg·L^{-1})	F/(mg·L^{-1})	NH_3-N/(mg·L^{-1})	COD_{Mn}/(mg·L^{-1})
NESSW	IV	0.1	1.5	1.5	10
	V	0.1	1.5	2.0	15
NESGW	I	0.005	1.0	0.02	1
	II	0.01	1.0	0.02	2

approach used in this study is illustrated in Fig. 2(a). The linkage of the surface water and groundwater models is shown in Fig. 2(b).

3 Model development

3.1 Selection of surface water quality model and groundwater model

The linked surface water and groundwater model was developed by linking the following three models: Water Quality Analysis Simulation Program (WASP), Modular Finite-Difference Groundwater Flow Model (MODFLOW), and Modular 3-D Transport Model (MT3D). WASP was first developed in 1981 as a tool for interpreting and predicting water quality responses to natural phenomena and pollution for various water quality management decisions. The model has been used widely after its development, and has been updated frequently by the US Environmental Protection Agency (US EPA) [24]. It has been used widely in water quality simulations for rivers, lakes, reservoirs, and bays [25–28]. WASP contains two general submodels: TOXI for toxicants, and EUTRO for conventional water pollutants. The governing mass-balance equation for water quality indicators is expressed as:

$$\frac{\partial C}{\partial t}+\frac{\partial(uC)}{\partial x}+\frac{\partial(vC)}{\partial y}+\frac{\partial(wC)}{\partial z} =\frac{\partial}{\partial x}\left(K_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right)+S_c, \quad (1)$$

where C is the concentration of a water quality indicator; u, v, and w are the velocity components in the x, y, and z directions, respectively; K_x, K_y, and K_z are the turbulent diffusivities in the x, y. and z directions, respectively; and S_c represents the internal and external sources and sinks per unit volume.

MODFLOW is a computer model that simulates three-dimensional groundwater flow through a porous medium, using a finite-difference method originally documented by McDonald and Harbaugh [29]. As with most computer programs that are used over a long time period, MODFLOW has undergone several major updates [29]. MT3D is a popular solute transport model that interfaces with MODFLOW, and was included for simulating the contaminant plume development [30]. The combination of MODFLOW and MT3D is used widely in many ground water simulation programs [31]. The partial differential equation for groundwater flow is expressed as:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W =S_s\frac{\partial h}{\partial t}, \quad (2)$$

where K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z directions respectively; h is the potentiometric head; w is a volumetric flux per unit volume representing sources and sinks; S_s is the specific storage of the porous material; and t is the time.

The partial differential equation describing the fate and transport of contaminants of species in 3 dimensional, transient groundwater flow systems can be expressed as follows:

$$\frac{\partial(\theta C_k)}{\partial t} =\frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial C_k}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(\theta \nu_i C_k)+q_s C_{sk}+\sum R_n, \quad (3)$$

where θ is the porosity of the subsurface medium; C_k is the dissolved concentration of species k; t is the time; X_i is the distance along the respective Cartesian coordinate axis i; D_{ij} is the hydrodynamic dispersion coefficient tensor; v_i is the seepage or linear pore water velocity along axis i; q_s is the volumetric flow rate per unit volume of aquifer representing fluid sources and sinks; C_{sk} is the concentration of the source or sink flux for species k; and R_n is the chemical reaction term.

3.2 Spatial conceptualization

Spatial conceptualization included both surface water conceptualization and groundwater conceptualization. In the surface water conceptualization, the simulated area was the Chaobai River from Xiangyang Sluice to Henan Village, which is 74000 m in length. As the river is relatively narrow, and the inflow and outflow are not complex, the river was conceptualized as a one-dimensional mesh in which the dam or sluice is the control node,

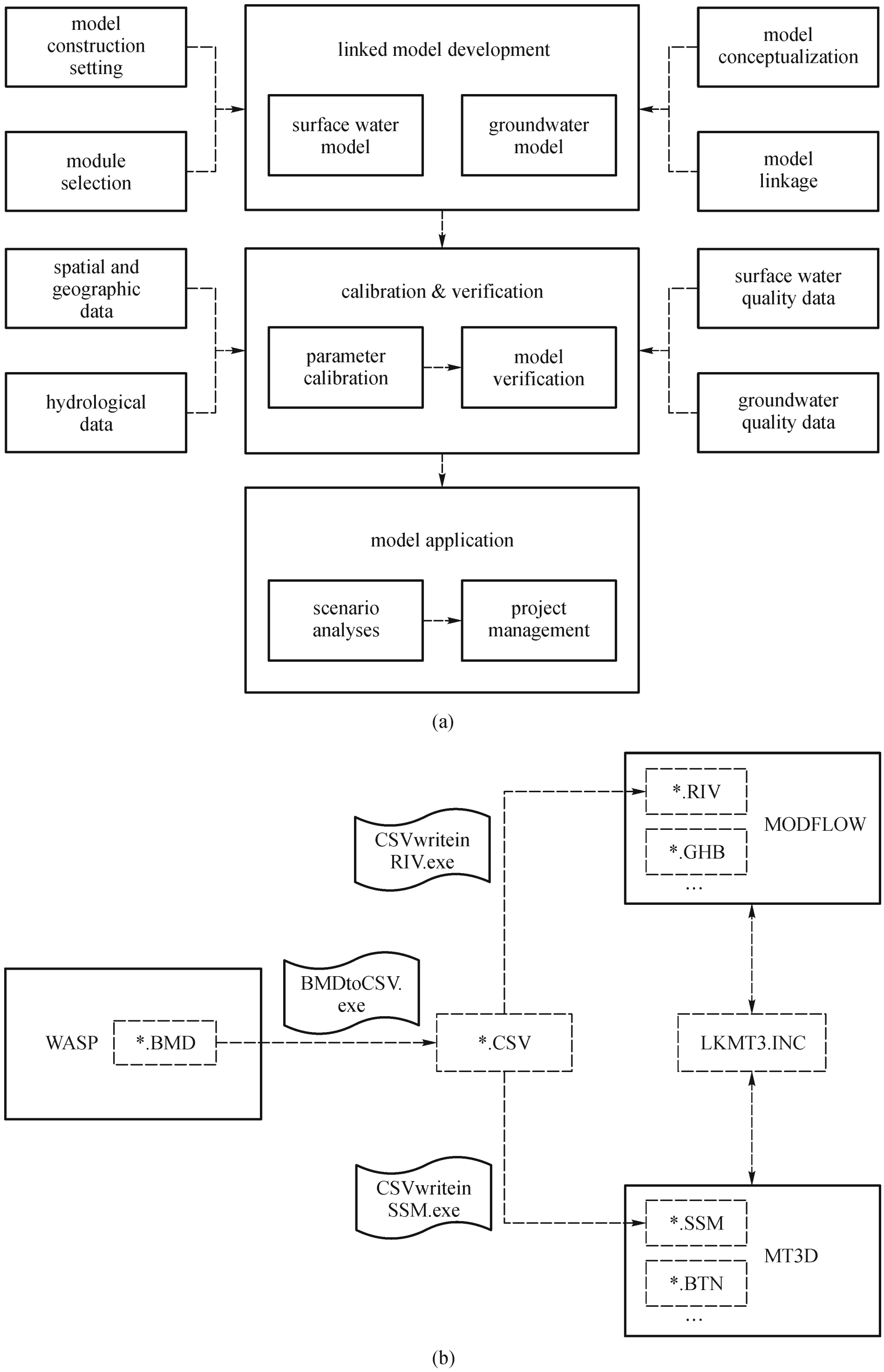


Fig. 2 Technical approach used in the project: (a) the framework of this project; (b) the linkage of the coupled model

and grids were set between the control nodes. The river was divided into a total of 38 rectangular cells, each 200 m long, as shown in Fig. 3(a).

The ground water conceptualization was more complex than that for the surface water. It included identifying the simulated area, the geological stratification setting, and cell division. Because many agricultural water wells pump mixtures of water from different aquifer layers, caused by fissures between layers, the various confined aquifer waters can be exchanged. Therefore, the several confined aquifers can be generalized as a single aquifer. Thus, the entire aquifer group was generalized as a transfluent phreatic-confined aquifer system. An orthogonal grid was used in the conceptualization. The simulated range size was 36 × 28 km horizontally. In the vertical, the actual depth of water wells was set to 200 m based on actual conditions. In accordance with the geological characteristics, the study area was divided into three parts (I-sand and gravel, II-sand, III-silty fine sand). Since the range was large, a trade-off between accuracy and computational efficiency of the simulation needed to be taken into consideration. Referring to the results of previous studies [32,33], the length and width of the grid were determined to be 500 m. The vertical grid scale was determined according to the actual thickness of the aquifer: the phreatic aquifer was set to 40–60 m, the impermeable layer set to 3–20 m, and the remainder set to the thickness of the confined aquifer, as shown in Fig. 3(b).

3.3 Boundary conceptualization

The simulation area was located on the northern end of the North China Plain, and lateral runoff from mountains is an important source of recharge for the groundwater. According to monitoring data obtained in recent years, there is rarely any water exchange between the eastern and western border. Thus, the eastern and western borders were conceptualized as confining boundaries, and the northern and southern borders were conceptualized as constant flow boundaries. The lateral runoff pollutant concentration data were obtained through local groundwater quality monitoring.

3.4 Linking the surface water and groundwater models

WASP outputted time series simulations of one-dimensional flow and water quality, such as water level and pollutant concentration. With the infiltration of surface water and pollutants, both the water and pollutants can intrude into the groundwater. Therefore, the flow properties and water quality of the surface water, particularly water level, water volume, and pollutant concentration, are of vital importance to MODFLOW as inputs. A program (BMDtoCSV.exe, obtained from the WASP development team) was used to transfer *.BMD, which is the output file of WASP, to *.CSV (Comma Separated Values). A program (CSVwriteinRIV.exe) was developed to fetch information on water level from *.CSV and write it in *.RIV, which is the input file of MODFLOW. A program (CSVwriteinSSM.exe) was developed to fetch information on pollutant concentration from *.CSV and write it in *.SSM of MT3D. LKMT3.inc was used to link the MODFLOW and MT3D, which was recommended by Zheng [30]. The linkage of the surface water and groundwater models is shown in Fig. 2(b).

3.5 Model calibration and verification

As the diversion project had not yet been initiated, and the Chaobai River was dry from Xiangyang Sluice to Henan village, no water quality monitoring data were available for surface water model calibration. However, a few models have been developed, using WASP, to simulate the rivers located in the Beijing plain area in recent years. These rivers, near the Chaobai River, have the similar hydrology, meteorology, and ecology conditions to those for the Chaobai River. Thus, the parameters for the surface water model were set by referring these models [25,26].

The main parameters to be set in the hydrogeological module of the groundwater model include permeability, specific yield, storativity, porosity, and soil bulk density. The baseline data was obtained from monitoring of seven water wells shown in Fig. 3(b) between 2003 and 2005. Based on the water levels of monitoring wells 1, 2, 4, and 7, and adjusting parameters based on past experiences, the error between simulated values and measured values was minimized.

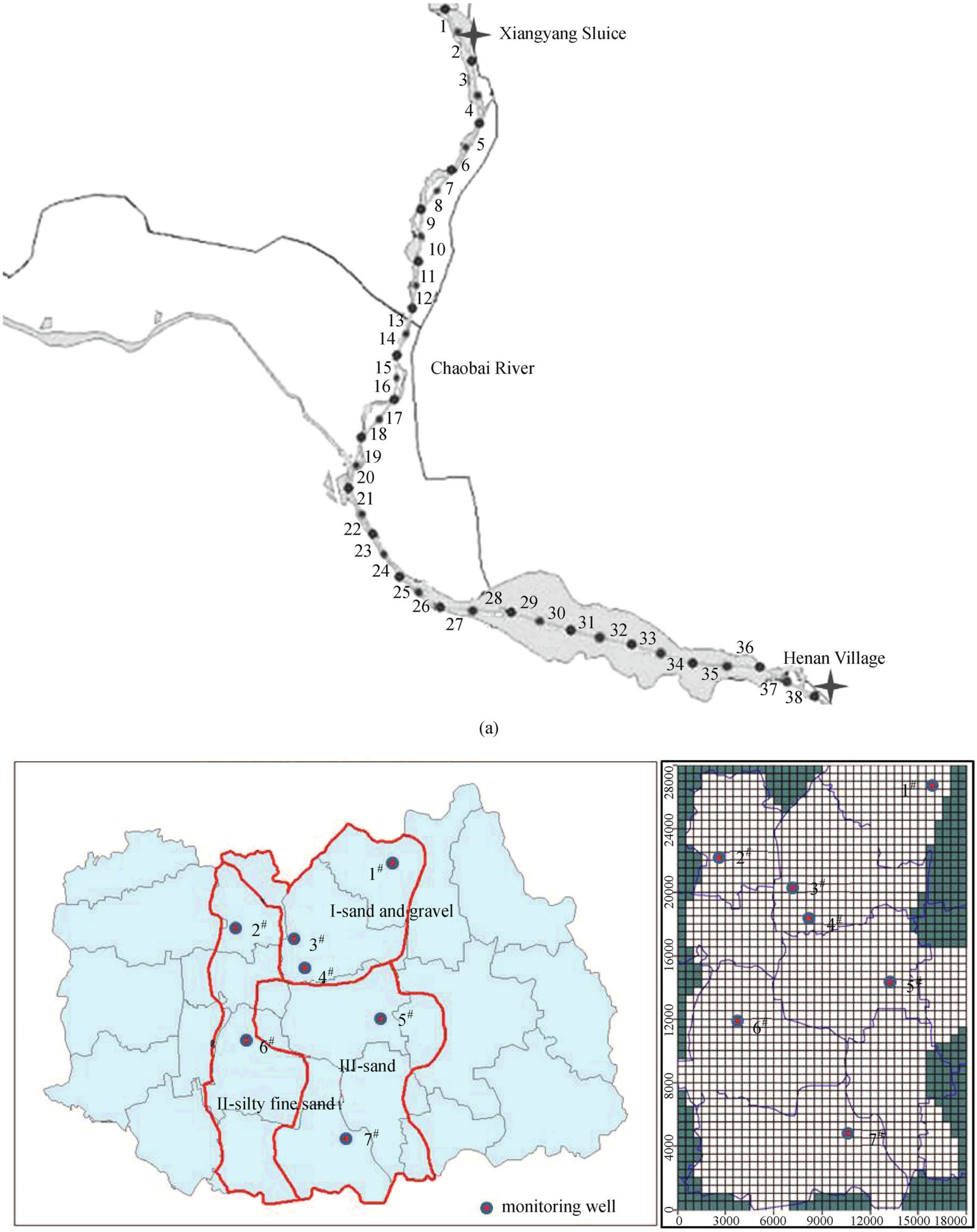
A trial-and-error method was used to calibrate the parameters and verify the models of both hydrogeology and water quality. The median error, which reflects the difference between simulated and observed monthly values, was used to evaluate the model calibration. The formulation for the median error is as follows:

$$E = 0.6745\sqrt{\Sigma\left(\frac{O-P}{O}\right)^2/(n-1)}, \tag{4}$$

where E is the median error, n is the number of observed points, O is the observed value, and P is the simulated value on the day of observation.

Based on the monitoring data from wells 1, 2, 4, and 7, the parameters were adjusted to minimize the mean error of the simulated and monitored water level values, and the water levels from monitoring wells 3, 5, and 6 were applied for verification. The statistical results are listed in Table 2 and typical monitoring well values are shown in Figs. 4(a) and 4(b).

For the calibration of water quality parameters, related studies were considered to set the range of model parameters. As the groundwater quality is relatively stable and without pollution from the outside, the parameters



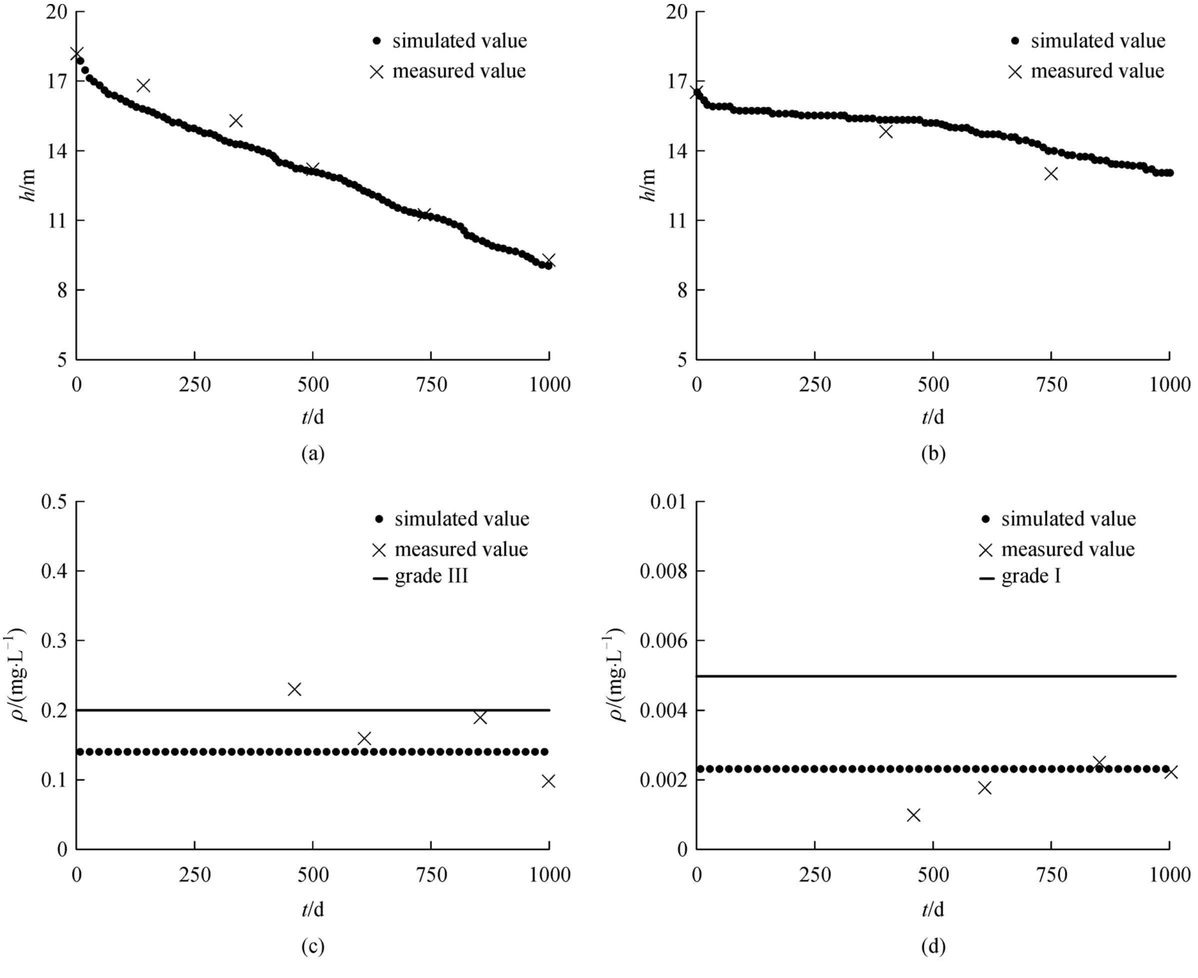
(a)

(b)

Fig. 3 Spatial conceptualization: (a) the surface water; (b) the groundwater

Table 2 Statistics of calibration for ground water

monitoring well	mean error/m	mean square deviation/m	median errors/%
1#	0.885	1.217	4.45
$2^{\#}$	1.239	1.535	8.41
$3^{\#}$	0.462	0.765	3.59
$4^{\#}$	0.448	0.806	5.14
$5^{\#}$	0.564	0.974	4.69
$6^{\#}$	0.542	0.771	3.00
$7^{\#}$	0.610	0.918	4.25
average	0.676	0.998	4.79



(a) (b)

(c) (d)

Fig. 4 Simulated and measured water levels and pollutant concentration: (a) water level, monitoring well $3^{\#}$; (b) water level, monitoring well $5^{\#}$, (c) As, monitoring well $3^{\#}$; (d) NH_3-N, monitoring well $3^{\#}$

were set to ensure the concentration range was invariant and reasonably without pollution. The verification results of monitoring well $3^{\#}$ are shown in Figs. 4(c) and 4(d), with As and NH_3-N as examples.

The results of calibration and verification demonstrated that the linked model provides a good platform for scenario analysis on the impact of hydraulic changes of the surface water flows on the groundwater, including the impact of a water transfer project to fill a seasonally dry channel.

4 Scenario analysis and discussion

After a comprehensive analysis of the major environmental problems that could be caused by the trans-basin water diversion project, three scenarios were devised and analyzed: the basic scenario, Scenario 1 (the first-stage project), and Scenario 2 (the second-stage project).

The basic scenario refers to the current conditions. In this scenario there is no trans-basin water diversion project, and the Chaobai River is dry. Scenario 1 refers to the conditions after the implementation of the first-stage trans-basin water diversion project. In this scenario, ~110000 $m^3 \cdot d^{-1}$ of treated water is diverted to the Chaobai River, with $40 \times 10^6\,m^3$ of water diverted annually. Scenario 2 refers to the conditions after the implementation of the second-stage trans-basin water diversion project. In this scenario, $60 \times 10^6\,m^3$ of water is diverted annually.

4.1 Basic scenario: current conditions

As shown in Figs. 5(a) and 5(b), in the basic scenario, the model simulated the groundwater flow field, including the flow direction and groundwater level, in each grid. The results show an obvious funnel in the northern part of study area because of the large-scale overexploitation of groundwater. The depth of the funnel increased and the range expanded continually in the five simulated years. The Southern District funnel was further enlarged because, due to the relatively low aquifer permeability coefficient, and it was difficult to restore the drawdown of groundwater level caused by overexploitation. The result clearly show that northern and central waters flow to the fountainhead, and that waters in the southern region slowly flow to the southern boundary, due to geological conditions. The phreatic water level is higher than the confined water layer, overall, so percolation could occur though the impermeable aquifer. Because the impermeable aquifer was thick and the permeability coefficient was low, recharge became relatively rare. The analysis showed that the water exchange between the confined aquifer and the phreatic aquifer is not significant, and that the groundwater was mainly exchanged within the same aquifer. The quality of water in this situation is good, despite the fact that the NH_3-N quantity slightly exceeds the standard.

4.2 Scenario 1: the first-stage project

As shown in Figs. 5(c) and 5(d), in Scenario 1, after five simulated years, groundwater levels rose significantly toward the storage reach of the river as a result of the diversion project. Water level changes appeared to be more significant in the phreatic aquifer than in the confined aquifer, and more significant in the north than in the south. In the first year, infiltration was simulated as $37.5 \times 10^6\,m^3 \cdot a^{-1}$, and in subsequent years the infiltration trended at ~$32 \times 10^6\,m^3 \cdot a^{-1}$. The infiltration quantity composed 84.2% of the total diversion quantity. The pollutants spread outward from the storage reach of the river, and the diffusion rate tended to decrease year by year. The results showed that pollutant levels changed by less than 0.9% in all concerned regions of the confined aquifer. The results indicated that the groundwater sources would not be contaminated.

4.3 Scenario 2: the second-stage project

In this scenario, the phreatic water level rose markedly, and the confined water level rose to a lesser extent. Both the phreatic and confined waters flow from south to north. In the water quality simulations, pollutants infiltrated and spread in the phreatic aquifer around the river, but only impacted a range of 2 km along the sides of the storage reach of the Chaobai River. The results showed that the pollutant concentration changes in all concerned regions were less than 4%, and the confined aquifer water quality reached grade I of the NESGW. The water of groundwater sources was not contaminated, as shown in Fig. 6.

5 Conclusions

A linked surface water and groundwater model, which focused on the impact of hydraulic changes of the surface water flows on the groundwater, was developed in this study. The results of the surface water simulation were used as the input for the groundwater simulation. Water levels and concentration of four contaminants (NH_3-N, COD_{Mn}, F, As) were simulated. The groundwater flow model was calibrated by matching simulated water levels with observed data, with an average median error of 4.79%, and the solute transport model was calibrated to ensure the stability and rationality of groundwater quality. The results of calibration and verification showed that the linked model developed in this study provides a good platform for simulating the impact of hydraulic changes of the surface water flows on the groundwater. With constant background and boundary conditions, scenario analysis was performed to quantify the impact on the groundwater environment from surface water seepage. The results showed that the concentrations of pollutants in all concerned regions changed slowly and that the water quality of groundwater sources was not significantly affected.

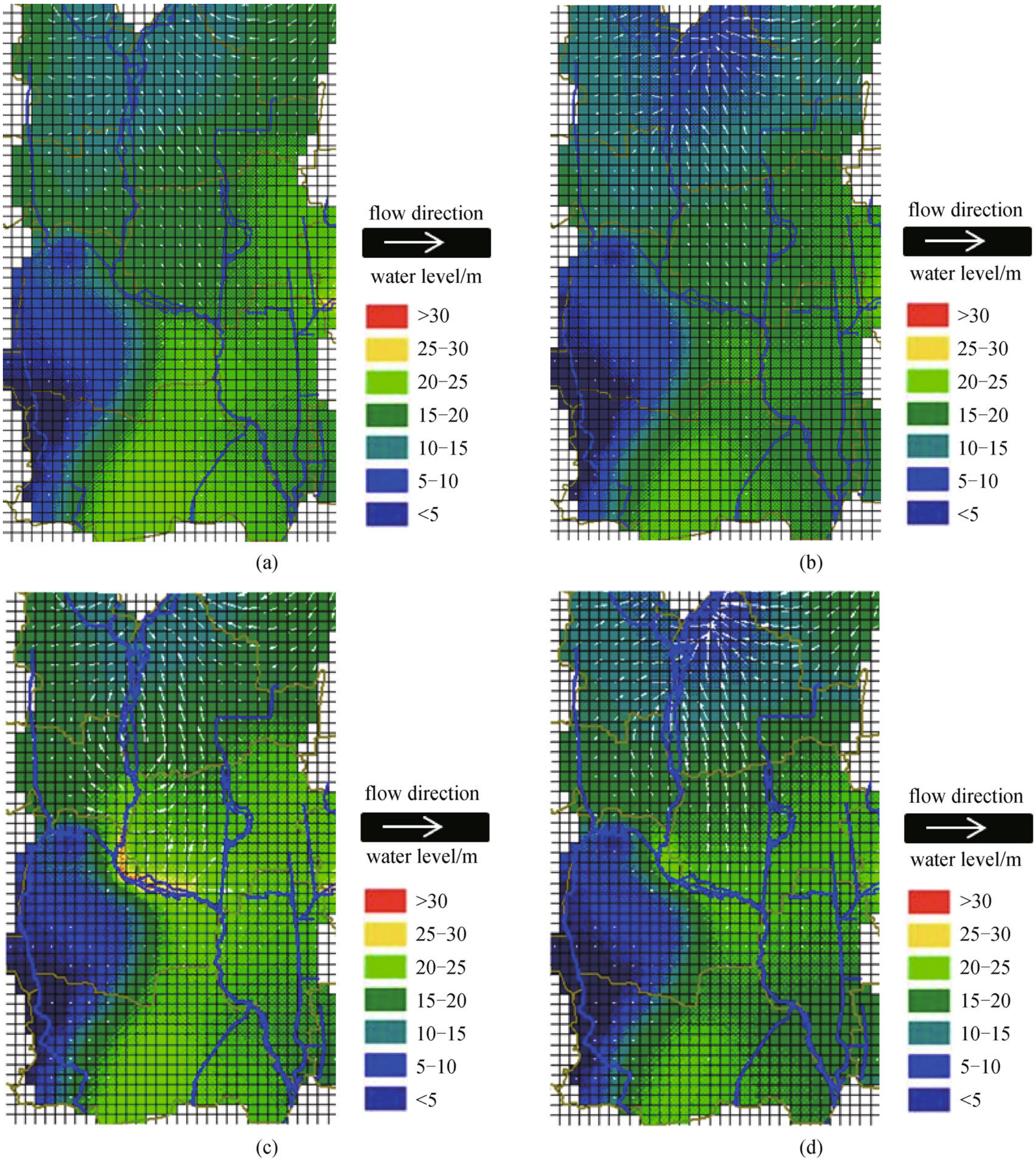


Fig. 5 Flow field and groundwater levels after five years: (a) the basic scenario, phreatic aquifer; (b) the basic scenario, confined aquifer; (c) the first-stage project scenario, phreatic aquifer; (d) the first-stage project scenario, confined aquifer

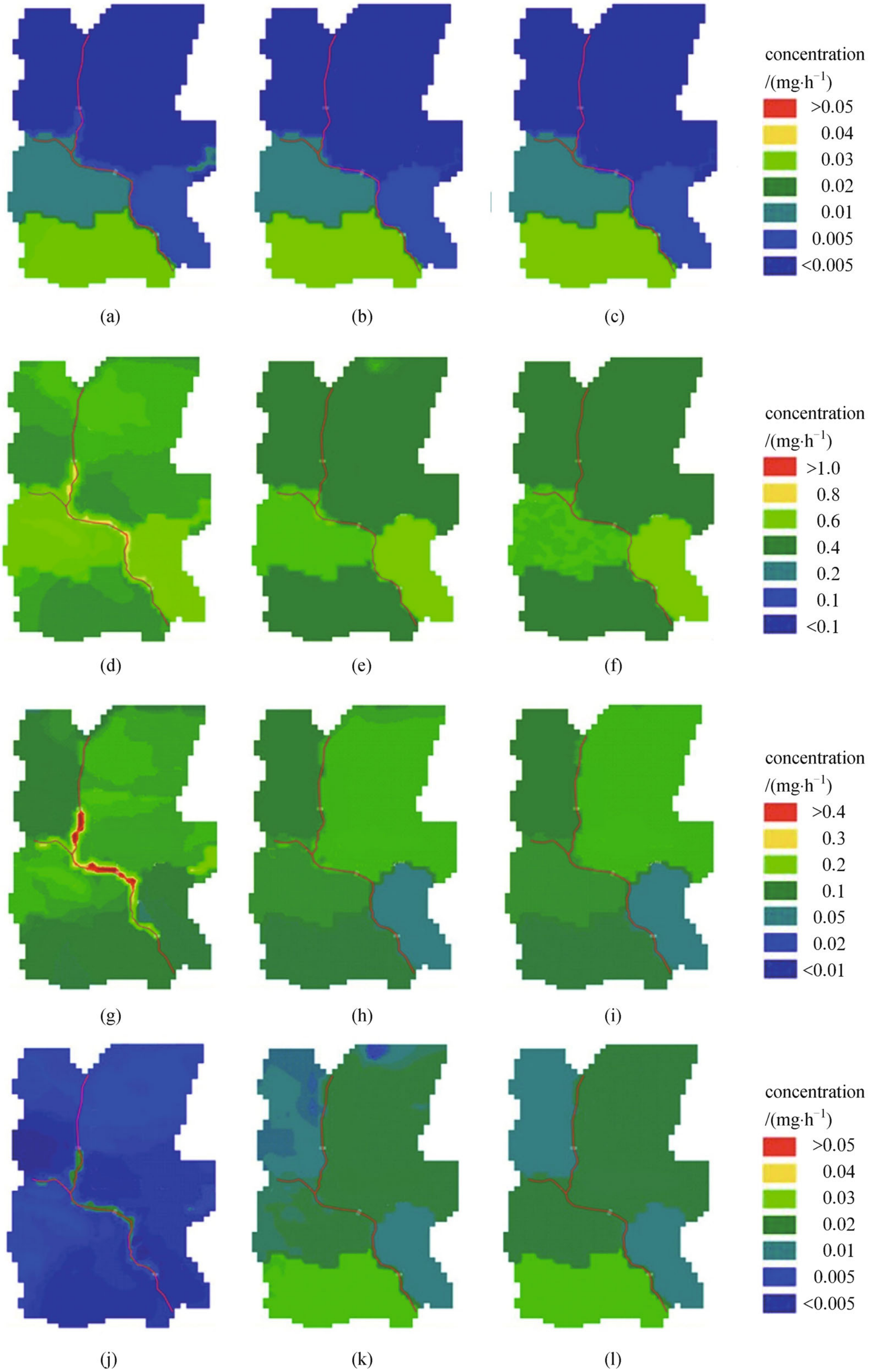


Fig. 6 Groundwater constituent concentrations after five years in the second-stage project scenario: (a) As, phreatic aquifer; (b) As, impermeable aquifer; (c) As, confined aquifer; (d) F, phreatic aquifer; (e) F, impermeable aquifer; (f) F, confined aquifer; (g) NH_3-N, phreatic aquifer; (h) NH_3-N, impermeable aquifer; (i) NH_3-N, confined aquifer; (j) COD_{Mn}, phreatic aquifer; (k) COD_{Mn}, impermeable aquifer; (l) COD_{Mn}, confined aquifer

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