

# Groundwater deterioration in Nankou—a suburban area of Beijing: data assessment and remediation scenarios

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**Abstract** Since the 1980s, high-nitrate concentration in one of the groundwater sampling wells at the Nankou site, northwest of the Beijing Plain, has become a major concern for the local water authority. In a previous study (Sun et al. in *Environ Earth Sci* 64(5):1323–1333, 2011), a hydrogeological structural model was developed based on the borehole logs of this area and the steady, as well as transient groundwater-flow models, were calibrated using the measured hydraulic heads. In this paper, the potential pollution sources in this area are investigated. The chemical analysis of the groundwater is also presented. The results demonstrate that the most likely pollution source is the untreated wastewater discharge from a nearby fertilizer factory. Furthermore, a mass transport model is developed to reproduce the nitrate transport process in the aquifer at the Nankou site under different pollution sources, i.e., a fertilizer factory, river with wastewater and an agriculture field. The combined effects of the river and agriculture fields present a better understanding of the nitrate transport in the local aquifer. In addition, a pumping scenario is designed to clean up the current nitrate concentration. The

pumping rate and the well location are first estimated with 2-D analytical solutions of the type curves method. Then a 3-D numerical model is used to calculate the nitrate-concentration changes after the pumping activities start. In the downstream direction of the regional groundwater flow, three pumping wells are set up for the clean-up strategy. The calculated pumping rate in each well is about 1,500 m<sup>3</sup>/day. After 1 year, the nitrate concentration in the observation well recedes to 68 mg/l from the initial value of 72.9 mg/l, and it will be lower than the limitation value (20 mg/l) after 5,400 days of groundwater extraction. The data assessment and clean-up scenarios reported in this paper are fundamental for the contaminated aquifer management in the future.

**Keywords** Nitrate transport modeling · Pollution sources assessment · Remediation scenarios · Nankou

## Introduction

Nitrate concentrations in groundwater that exceed the maximum contaminant level (MCL) of 10 mg/l NO<sub>3</sub>-N established by the US Environmental Protection Agency have been reported in many countries such as UK (Zhang and Hiscock 2011), Germany (Strebel et al. 1989), USA (Hudak 2000) and China (Zhang et al. 1996). A survey in 2005 of groundwater quality conducted by Beijing Hydrological Center (BHC) and Changping Water Authority in the Changping District of Beijing shows that nitrate-N concentrations in 4 of the 78 sampled wells have exceeded 20 mg/l (MCL value established by Chinese government), with the highest value of 55.6 mg/l in well #346 (see Fig. 2 for the location). The primary health hazard from drinking water with nitrate-nitrogen occurs

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when nitrate is transformed to nitrite or nitrosamine in the digestive system. Nitrite is known to cause methemoglobinemia in infants, while nitrosamine is carcinogenic and may play a role in the induction of certain gastrointestinal cancers (Fan et al. 1987).

Agricultural activities related to the fertilizer application are possibly the most significant anthropogenic sources of nitrate contamination in the groundwater (Saffigna and Keeney 1977; Ju et al. 2006). Observed pollution may be the consequence of farming practices many years ago rather than current pollutant sources (Singh and Sekhon 1979). According to the historical chronology of the Changping District (Zhao and Sun 1979), there was a fertilizer factory (see Fig. 10c for the location) founded in 1974, about 8 km from the center of the Changping District with an annual output of 15,000 tons of synthetic ammonia. The untreated wastewater containing high-concentration ammonium [about 250 mg/l, estimated from the discharge standard of water pollutants for the ammonia industry (GB8978-88) of China] was directly discharged to the nearby Guangou stream through an underground pipe. Assuming the amount of wastewater discharge is 150 m<sup>3</sup>/t (synthetic ammonia), the total ammonium emission from the factory amounts to 562 ton/a. In 1990, the factory stopped manufacturing fertilizer. Therefore, in the 17 years (1974–1990) the fertilizer factory was operational it was a potential pollution source for groundwater in the area.

The identification of areas with high-nitrate concentration is important for the local water authority and is essential for developing a remediation strategy. Once such high-risk areas have been identified, remediation measures can be implemented to reduce or remove the contamination plume in the aquifer. Existing remediation strategies for nitrate-contaminated groundwater can be classified into the following three categories: (1) cut-off walls at the contamination sources, diverting groundwater flow from passing through the waste (Loxham and Westrate 1985; Anderson and Mesa 2006), (2) permeable reactive barriers with a reductant such as zerovalent iron to degrade groundwater nitrate via autotrophic or heterotrophic denitrification by microorganisms (Till et al. 1998; Su and Puls 2007; Hunter 2001), and (3) pump-and-treat systems to remove the contaminated groundwater so that it can be treated at the surface with the conventional methods (Cheremisinoff 1998; Matott et al. 2006; Baú and Mayer 2008). Natural attenuation is an alternative remediation concept for organic compounds (Beyer et al. 2006).

In the previous study (Sun et al. 2011), a high-resolution 3-D groundwater flow model was developed for the Nankou area with the simulator OpenGeoSys (OGS) (Kolditz and et al. 2012). The model was calibrated with all available data, and the groundwater-flow regime was investigated under steady and transient conditions. This detailed 3-D

groundwater flow model serves as a base for the mass transport and the remediation scenario analysis in this paper.

The main objectives of this paper are to (1) test the 3-D integrated mass transport model combining different pollution sources in the Nankou area; (2) analyze the impact on the groundwater flow model by heterogeneous hydraulic conductivity fields with uncertainty; (3) develop the pumping scheme for the removal of the groundwater with high-nitrate concentration.

## Groundwater quality characterization

In the most suburban districts of the Beijing area, only rare measurements for groundwater quality are available. In general, there are 2–3 samples analyzed for each suburban district in April (dry season) and September (flood season) since the 1970s to report on the groundwater quality of Beijing City. The following data analyses are based on these routine measurements.

### Nitrate in the Nankou site

The limitation value of nitrate–N for drinking water sources is 20 mg/l according to the national Quality Standard for Ground Water (QSGW, GB/T 14848-93) in China. The long term (1980–2010) groundwater quality trend (Fig. 1) is identified in sampling well #346. Compared with the QSGW criterion, most of the nitrate concentrations in the flood season are over 20 mg/l. After 1995, all measurements exceed the limitation value and are still increasing in both flood and dry seasons.

To ascertain the current state of nitrate in the aquifer around well #346, a groundwater quality-monitoring network (Fig. 2) was established in 2009, including a total of 16 sampling wells. The measurements in this monitoring

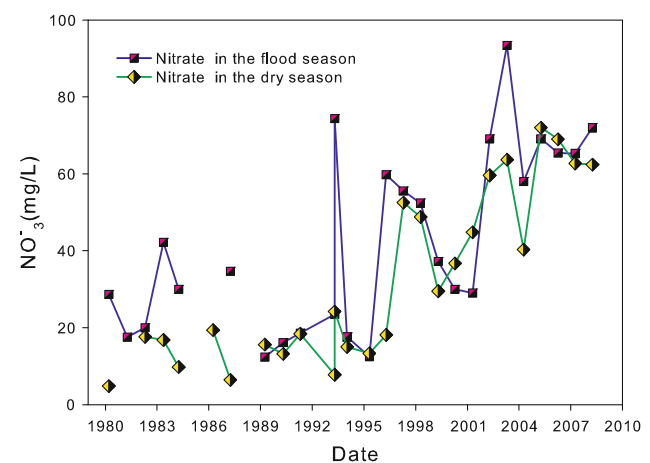
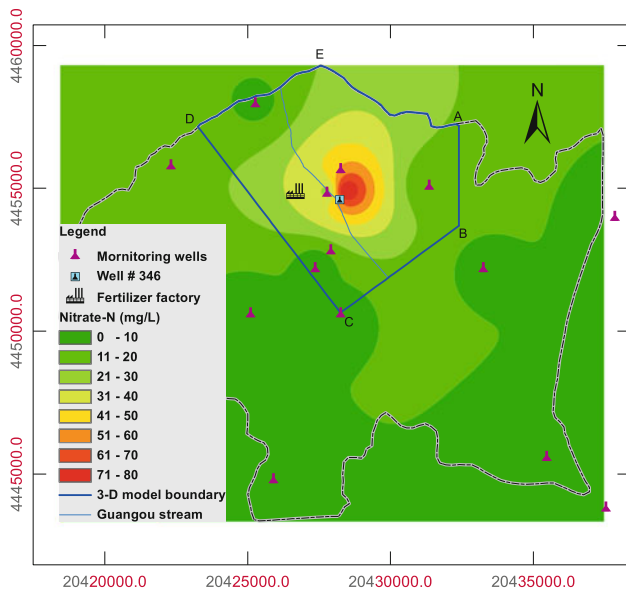


Fig. 1 Long term nitrate trend in sampling well #346



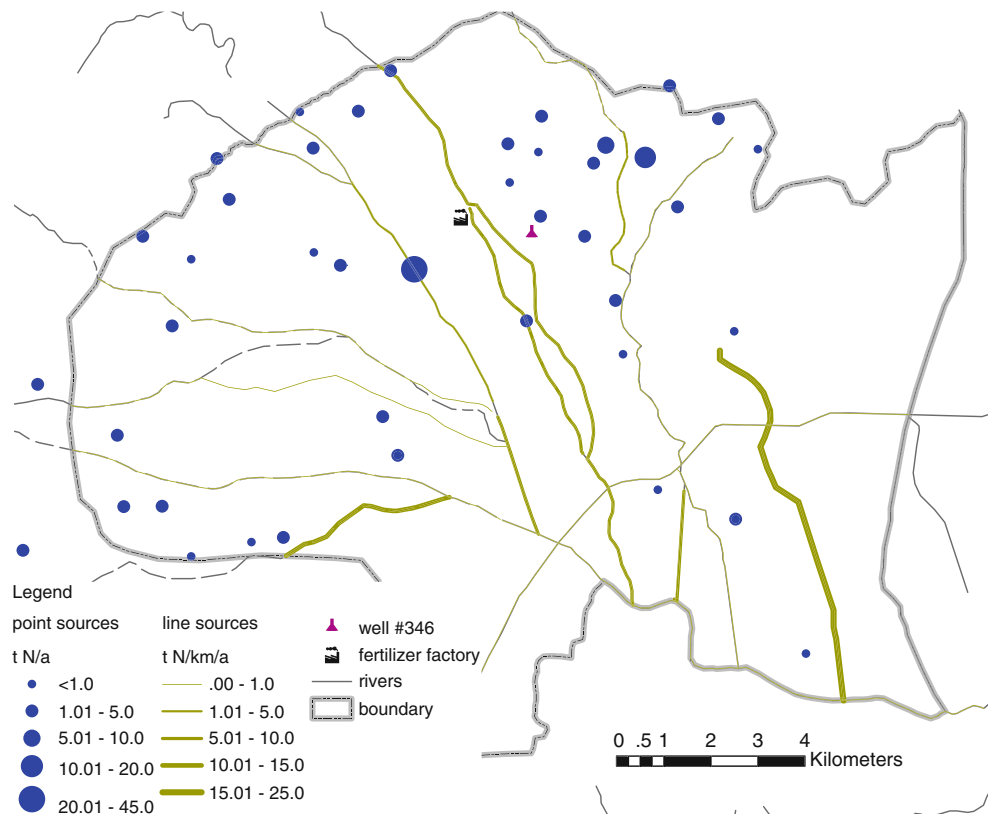
**Fig. 2** Nitrate at the Nankou site in Feb. 2010

network show that the nitrate concentrations in the wells, about 4 km distance apart, are still below the safe limitation.

Potential pollution sources

Groundwater contamination can occur in many ways and from various sources, both natural- and man-made. The

**Fig. 3** The distribution of potential pollution sources to the aquifer



greatest amount of concern regarding groundwater contamination within the study area has centered on the pollution associated with human activities. Human-induced groundwater contamination can be related to the following six categories: abandoned wells, waste disposal sites, agricultural activities, livestock and poultry waste, industrial wastewater and residential sewage.

1. Abandoned wells

Most pumping wells (614) in the Nankou area are utilized to supply drinking water or irrigation. Only 40 wells are abandoned due to varying reasons. All of the abandoned wells are sealed completely and therefore not considered as potential paths for the regional aquifer pollution.

2. Waste disposal sites

There are six waste disposal sites in the study area, and all of them are distributed inside of the Machikou town (Fig. 3). These waste disposal sites began operating in 2006 or 2007. The total amount of disposed waste from the above sites is about 19,310 m<sup>3</sup>/year. The leachate from these waste disposal sites is a potential threat to the regional aquifer.

3. Agricultural activities

According to the land use distribution of the Nankou site, irrigated agriculture field accounts for 22% (43.45 km<sup>2</sup>) of the total land area. The water for irrigation is mainly from the local aquifers. The intensive

fertilization of farmlands and orchards (Fig. 4) brings excessive amounts of nitrate to the vadose zone. The average applied fertilizer is 210 kg N/(ha · a) and inorganic-nitrogen accounts for 61%.

#### 4. Livestock and poultry waste

Livestock wastes can either be solid or liquid. Livestock waste is described as liquid if the moisture content is more than 96%, slurry if between 90 and 96%, and if it is below 84% it is considered solid. The solid waste is normally used as soil conditioner in this area, and the liquid waste is also irrigated as organic fertilizer in the farmlands. Many farmers discharge their untreated sewage to nearby streams and canals, which results in the pollution of regional shallow aquifers. Table 1 shows the populations of livestock and poultry in the towns of the Nankou area and Fig. 3 shows their distribution.

#### 5. Industrial and enterprise sewage

There are in total 109 factories or enterprises in the study area, and most of the wastewater is treated before it is discharged to the Beishahé stream. However, still 17 factories or enterprises are discharging the untreated wastewater into nearby streams or channels. The discharged untreated wastewater accounts for 84.6 tons of ammonium ( $\text{NH}_4^+$ ) per year.

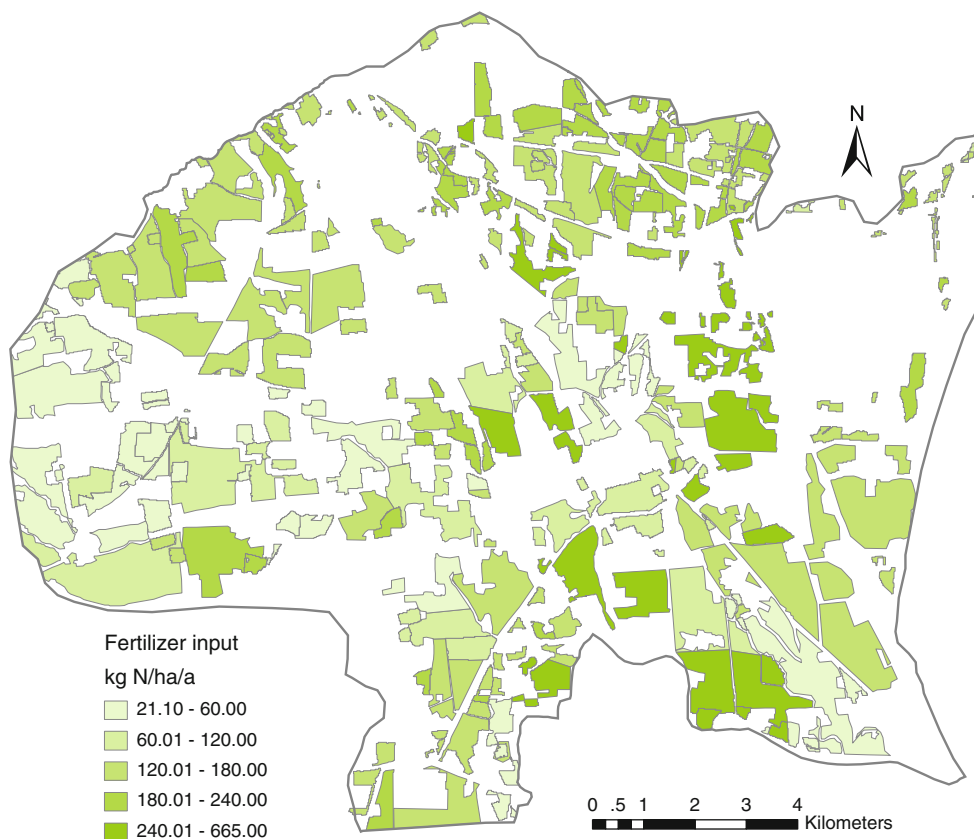
#### 6. Residential sewage

According to the pollution-sources investigation, only 9.23% of residential wastewater is collected and conveyed to a central location for treatment or disposal in the study area. In other decentralized residential areas, the wastewater is disposed on-site or flows through the channel system into surface water bodies. The most dangerous strategy is to dispose the wastewater in unsealed pits, which are direct threats to the regional aquifer system. The total ammonium from the residential sewage accounts for about 119 tons per year.

Based on the above analyses, the nitrogen discharge by different sources could be placed in the following order: agricultural activities > livestock and poultry waste > residential sewage > industrial and enterprise wastewater > waste disposal sites.

#### Hydrochemistry

Chemical analysis of the groundwater samples from 1980 to 2010 in well #346 produces the statistical values as shown in Tables 2 and 3 (data collected from BHC). These results indicate that after 1995, the average concentrations



**Fig. 4** The distribution of fertilizer input to the farmlands and orchards

**Table 1** The populations and sewages of livestock and poultry in the Nankou area

Towns/animals	Pigs	Cattle	Chickens	Sewage (10 <sup>3</sup> kg/a)
Nankou	11,771	3,225	67,398	68,073
Chengnan	1,500	868	7,000	1,300
Machikou	1,500	198	120,578	14,446
Liucun	150	173	–	–
Shisanling	–	1,570	–	6,700
Total	14,921	6,034	194,972	88,519

**Table 2** Statistical parameters of the groundwater chemical analysis in well #346 (1980–1995)

Parameters	Unit	Mean	Minimum	Maximum	Standard deviation
pH	–	7.5	6.8	8.1	0.3
Hardness	mg/l	164	11	394	124
Diss. solid	mg/l	531	120	998	308
SO <sub>4</sub> <sup>+</sup>	mg/l	49.6	10.8	130.0	36.6
Cl <sup>–</sup>	mg/l	50.1	9.7	132	28.4
NH <sub>4</sub> <sup>+</sup>	mg/l	0.07	0.01	0.20	0.06
NO <sub>3</sub> <sup>–</sup>	mg/l	20.1	4.8	74.4	14.0
MnO <sub>4</sub> <sup>–</sup>	mg/l	0.92	0.20	2.60	0.54
E.C.	μS/cm	671	300	1,250	312

of hardness and nitrate in well #346 surpass the highest limits permitted for drinking water set forth by the QSGW criteria, 450 and 20 mg/l respectively. According to the land use distribution in the Nankou area, the nitrogen fertilizer application may increase the nitrate concentration in the groundwater directly or by the transformation from other nitrogen forms, e.g., ammonium. The hardness increment in the groundwater at the same time may be caused by the dissolution of some minerals bearing calcium and magnesium. This dissolution happens during the infiltration of wastewater bearing ammonium, because, nitrification of the ammonium changes the pH condition (Wang et al. 1998). The concentrations of the permanganate index in the groundwater of the Nankou site remain at a low level, which means there is less organic matter. In such a chemical environment, the denitrification processes dependent on the organic matter and heterotrophic bacteria can not take place due to the high dissolved-oxygen levels. Therefore, the nitrate transport through the saturated zones in the study area follows the advection-dispersion transport equation without degradation (Eq. 1) as those phenomena are considered to be small in comparison to other effects. Moreover only little information is available to quantify in-situ denitrification processes in the Nankou area.

**Table 3** Statistical parameters of the groundwater chemical analysis in well #346 (1996–2010)

Parameters	Unit	Mean	Minimum	Maximum	Standard deviation
pH	–	7.3	6.6	7.9	0.3
Hardness	mg/l	627.4	216	868	132
Diss. solid	mg/l	1,052	225	1,742	315
SO <sub>4</sub> <sup>2–</sup>	mg/l	94	42	156	23.7
Cl <sup>–</sup>	mg/l	134.9	68.4	219	34.8
NH <sub>4</sub> <sup>+</sup>	mg/l	0.2	0.05	0.58	0.15
NO <sub>3</sub> <sup>–</sup>	mg/l	54.8	18.1	93.4	19.35
MnO <sub>4</sub> <sup>–</sup>	mg/l	0.8	0.5	2.1	0.38
E.C.	μS/cm	1,241	245	1,850	401
Fe	mg/l	0.3	0.03	1.14	0.28
Diss.O <sub>2</sub>	mg/l	6.7	5.0	8.5	1.48
K <sup>+</sup>	mg/l	2.9	0.9	5.3	1.79
Na <sup>+</sup>	mg/l	45.4	21.4	94	30.53
Ca <sup>2+</sup>	mg/l	162.7	55.1	227	71.13
Mg <sup>2+</sup>	mg/l	185.8	19.4	460.14	239.39
CO <sub>3</sub> <sup>2–</sup>	mg/l	271.0	154	398	118.4

**Model setup**

In this study, both 2-D and 3-D contaminant transport models are developed for the Nankou site using the OGS simulator. With the 2-D approach, the heterogeneity of transmissivity at full scale is considered and the impact of the random transmissivity fields with uncertainty on the simulation results is also discussed. A rapid practical assessment for the pumping rate by analytical capture zone type curves method (Javandel and Tsang 1985) in 2-D case is applied for the remediation strategy design. However, the 3-D numerical model using the available data is necessary to investigate the contaminant transport in the vertical direction, and the 3-D visualization of the simulation results is more easily understood by stakeholders on site. Therefore the 2-D and 3-D models are set up, as each has certain advantages.

**Study area and discretization**

The model domain for the 2-D case is at the same scale with the previous groundwater flow model. The average aquifer thickness of 50 m is used in the 2-D simulation. Considering additional groundwater quality measurements available from nearby the well with high nitrate and the model running time consumption, the domain for the 3-D contaminant transport modeling is redefined as shown in Fig. 2 (polygon ABCDE).

Based on this local domain, a refined 3-D mesh is created with the method mentioned in the previous groundwater flow

model (Sun et al. 2011). The number of the horizontal triangle elements is 27,772. The vertical layers are created based on the borehole data. The total number of the prism and tetrahedron elements in the 3-D domain is 191,766.

### Governing equations

The partial differential equation that governs the three-dimensional transport of a single chemical constituent in groundwater, considering advection, dispersion, fluid sinks/sources without equilibrium-controlled sorption and first-order irreversible rate reactions is described in the following equation (Fetter 1998):

$$\frac{\partial C}{\partial t} = \nabla \cdot (\mathbf{D} \cdot \nabla C) - \nabla \cdot (\vec{v} C) + \frac{q_s}{\theta} C_s \quad (1)$$

where  $C$  is the dissolved concentration ( $\text{ML}^{-3}$ );  $\vec{v}$  is the pore water velocity vector ( $\text{LT}^{-1}$ );  $C_s$  is the concentration of the fluid source or sink flux ( $\text{ML}^{-3}$ );  $\mathbf{D}$  is the hydrodynamic dispersion tensor ( $\text{L}^2\text{T}^{-1}$ );  $q_s$  is the volumetric flow rate per unit volume of aquifer and represents fluid sources and sinks ( $\text{T}^{-1}$ ) and  $\theta$  is the porosity (—).

In Eq. (1), the nitrate transport requires the velocity of the groundwater flow ( $\vec{v}$ ). Therefore, it is necessary to develop a groundwater flow model to obtain the velocity field. A common formation of the groundwater flow equation (Freeze and Cherry 1979; Fetter 1998) in a confined aquifer with sources or sinks in a three-dimension is:

$$S_s \frac{\partial h}{\partial t} = \nabla \cdot (\mathbf{K} \nabla h) - W \quad (2)$$

where  $\mathbf{K}$  is the hydraulic conductivity tensor ( $\text{LT}^{-1}$ ) in three orthogonal directions,  $h$  is the hydraulic head (L),  $W$  is the volumetric flux per unit volume ( $\text{T}^{-1}$ ) and represents the groundwater recharge/discharge, i.e., source/sink term for groundwater,  $S_s$  is the specific storage capacity ( $\text{L}^{-1}$ ) of the porous medium and  $t$  is the time. In our model,  $W$  is a function of space and time, depending on variations of recharge and discharge. The hydraulic head distribution can be computed when Eq. (2) is solved, and according to the Darcy's law, the groundwater velocity field is achieved.

The general equation for two-dimensional horizontal flow in an aquifer under the Dupuit–Forchheimer approximation (Bear 1972), allowing for heterogeneity and anisotropy in transmissivity can be described as:

$$S \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left( T_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( T_y \frac{\partial h}{\partial y} \right) + N \quad (3)$$

where  $S$  is the aquifer storativity (—);  $N$  represents the addition of water in the vertical direction (e.g., recharge) ( $\text{LT}^{-1}$ );  $T_x$ ,  $T_y$  is the transmissivity of the aquifer in  $x$  or  $y$  direction ( $\text{L}^2\text{T}^{-1}$ ).

### Parameter settings

In the field pumping test, the hydraulic conductivity  $K$  can be described by the specific capacity  $Q(\text{L}^3\text{L}^{-1}\text{T}^{-1})$  and the thickness of the aquifer  $M(\text{L})$  (Lan et al. 2004; Lan 2007) as:

$$K = \frac{Q}{M} \quad (4)$$

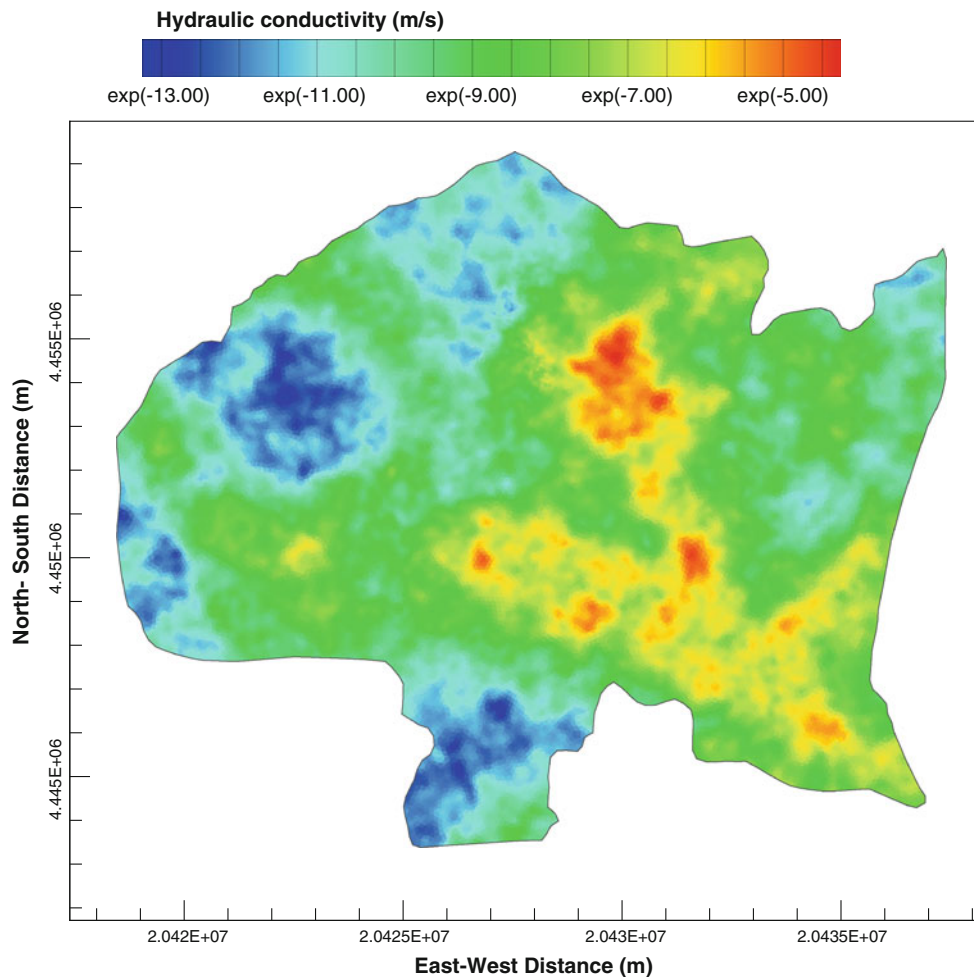
Therefore, with the available 20 pumping test data, the 2-D heterogeneous hydraulic conductivity field is generated based on the conditional Gaussian simulation using GSTAT (Pebesma and Wesseling 1998). Five random heterogeneous fields are realized in this study. For those five fields, the estimated hydraulic conductivity values in the same node are more or less different, but they are conditioned by the same available data and have equivalent statistical properties, i.e., spatial continuity (variogram) and frequency (histogram). Figure 5 shows the best fit heterogeneous hydraulic conductivity distribution which is used in the later 2-D mass transport simulation in the Nankou area.

For the 3-D model, the hydraulic conductivities in different materials are also taken from the calibration results in the previous groundwater flow model (Sun et al. 2011).

### Initial and boundary conditions

The simulations start with the same constant groundwater level (30 m) for both 2-D and 3-D groundwater (GW) flow models. The boundary conditions for the 2-D GW model are defined exactly as that described in Sun et al. (2011). For the redefined 3-D GW model, the boundaries DE and EA (Fig. 2) are the contact zones between the Beijing Plain Quaternary sediments and limestone formations of the mountain terrains, and there are lateral recharges horizontally flowing through these boundaries. The lateral fluxes through DE and EA boundaries are readjusted when the local groundwater flow model is calibrated against the observed groundwater levels. The AB and CD (Fig. 2) boundaries are prescribed with no flow conditions based on the regional groundwater flow analysis. The BC (Fig. 2) boundary is assigned with a general head boundary. The head values at the nodes along the BC boundary are calculated by linear interpolation between the observed head of the start point and that of the endpoint. The top boundary is the precipitation recharge and groundwater abstraction rates; the bottom boundary is assigned with no flow.

The initial nitrate concentration within the domain is set with 4 mg/l in the both cases based on the measured background values in the Nankou site.



**Fig. 5** The heterogeneous hydraulic conductivity ( $K$ ) distribution

**Results and discussion**

**2-D approach**

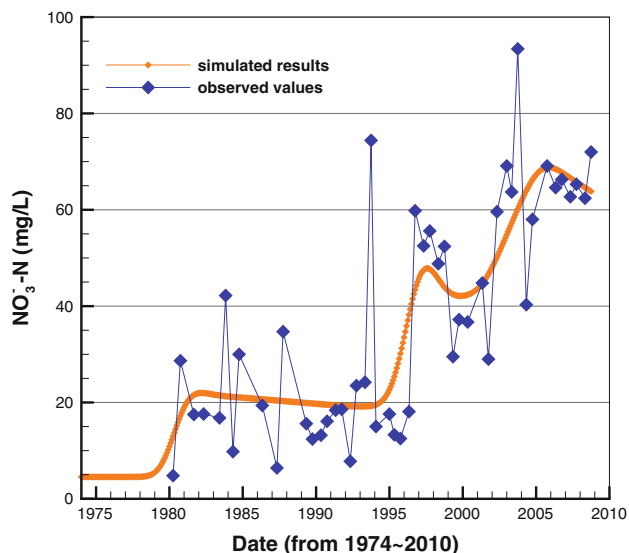
The nitrate transport in the 2-D heterogeneous hydraulic conductivity field is simulated with the pollution source being the fertilizer factory discharge. The nitrate discharge from the fertilizer factory and the dispersivities in Eq. (1) are estimated with PEST (Doherty 2004) by searching for the minimum value of the objective function, which is the sum of the squared deviation between the calculated and observed concentrations in well #346. The results of 1974–2010 are shown in Fig. 6.

Even though a good fit (Fig. 6) can be achieved with the inverse calibration in this 2-D mass transport model, the uncertainty of the heterogeneous hydraulic conductivity fields generated by the Gaussian simulation has an influence on the groundwater flow pattern. When the five calculated hydraulic conductivity fields are used to run the 2-D groundwater flow model utilizing the same discharges

and recharges, the calculated heads deviate from the observed values in different ways and in different magnitudes. The comparison between the calculated heads from the different simulations and the observed values are shown in Table 4 and Fig. 7. Simulation-2 indicates the best fit with the observed values, and the results of simulation-5 have the largest deviations from the observed values. The standard errors are also included in Fig. 7, which shows that five standard errors are below 2 m and the largest one is presented in well #344. Therefore, the relatively small number of the Gaussian simulation is not meant as a representative statistical analysis for the uncertainty assessment as done e.g., by Bauer et al. (2006) for a similar topic. However, it shows the model sensitivity and has to be continued in the future research.

**3-D approach**

The nitrate transport process in the horizontal direction can be realized in the 2-D case by substituting the hydraulic



**Fig. 6** Observed and simulated nitrate concentrations in well #346 as the result of 2-D model calibration (1974–2010)

conductivity with transmissivity in the groundwater flow model. The vertical changes in nitrate concentration are reflected in the 3-D modeling. In this study, the horizontal and vertical distributions of nitrate are presented in Fig. 8a–c. Fig. 8d is the vertical profile of materials at the same location of the profile in Fig. 8c, and the comparison of these two profiles shows that the transportation of the contamination plume slows down in the clay layer (red one). The clay layer can block the plume extension to the deeper aquifer, however, the pollutant will accumulate in the current aquifer layer and become a potential pollution source in the long term if there is no remediation strategy applied.

The calculated results shown in Fig. 8 are obtained under the scenario of the nitrate pollution source being only from the outlet of the fertilizer factory. The total simulation

period is 30 years. The discharge of nitrate from the fertilizer factory is estimated with the value of  $5.0 \times 10^6$  g/day under the assumption that most ammonium was oxidized into nitrate in the aquifer.

The study by Zheng and Bennett (2002) shows that the longitudinal and transversal dispersivities are dependent on the scale of the observation, which is defined as the distance between the observation points and the source. In our model, they are assigned with values of 50 and 10 m, respectively, by a trial-and-error method.

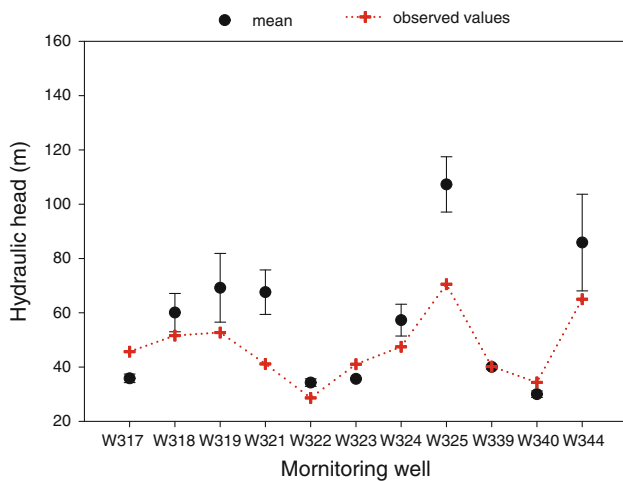
To identify the other contaminant sources and pathways, we investigated the potential pollution sources of this area in the past decades. After many interviews with the local farmers and water authority, it is ascertained that the agriculture fields adjacent to the Guangou stream were irrigated by the wastewater discharged from the fertilizer factory for 17 years since 1974. The major component of the wastewater ( $7.0 \times 10^5$  m<sup>3</sup> per year) from the fertilizer factory was ammonium, and discharged to the Guangou stream without any treatment. A pumping station was set up to take the wastewater from the Guangou stream for irrigation. The estimated nitrate permeated into the groundwater through the unsaturated zone amounts to about 37.5 g/(m<sup>2</sup> · a).

The Guangou stream is a seasonally losing stream. The high ammonium-concentration wastewater moves rapidly down through the river-bed consisting of coarse gravel and sand. According to the investigation report of BHC, the total wastewater leaching to the aquifer from the Guangou stream amounts to  $1.9 \times 10^5$  m<sup>3</sup> per year, including  $3.8 \times 10^4$  kg ammonium. In this study, a 3-D model with the stream and wastewater-irrigated fields as pollution sources is also set up to reproduce the contaminant transport pathways over time. The locations of the stream and the wastewater-irrigated fields in the 3-D model domain are shown in Fig. 10c.

**Table 4** Calculated hydraulic heads based on five heterogeneous hydraulic conductivity fields (unit: m)

Wells	Observed value	Simu_1	Simu_2	Simu_3	Simul_4	Simu_5	Mean	Standard error
W317	45.7	40.2	34.9	30.7	35.5	37.8	35.8	1.6
W318	51.6	46.9	48.0	66.9	54.0	84.5	60.1	7.1
W319	52.7	51.9	49.4	66.5	59.9	118.4	69.2	12.7
W321	41.1	60.3	41.9	77.6	67.4	90.6	67.6	8.2
W322	28.6	33.3	29.2	37.1	35.9	35.8	34.3	1.4
W323	41.0	36.0	36.0	35.4	35.2	35.4	35.6	0.2
W324	47.5	45.6	49.2	77.3	50.5	63.8	57.3	5.9
W325	70.5	126.7	71.1	107.3	104.4	126.9	107.3	10.2
W339	40.2	40.0	38.2	42.4	38.9	40.6	40.0	0.7
W340	34.4	30.2	30.8	30.2	32.9	25.6	30.0	1.2
W344	65.0	54.0	63.6	84.1	73.4	154.2	85.9	17.8
Standard error		61.4	13.7	68.6	46.6	139.5		





**Fig. 7** Standard errors of the 5 2-D groundwater flow simulation results and observed values

The nitrate plume evolution over 30 years is depicted at six different times in Fig. 9, and from the 18th year, the pollution sources are removed from the simulation as the fertilizer factory was closed at that time. The nitrate concentration contour can not be calibrated in these cases, because, only one time series of the nitrate concentration is available in this study area.

Remediation scenarios analysis

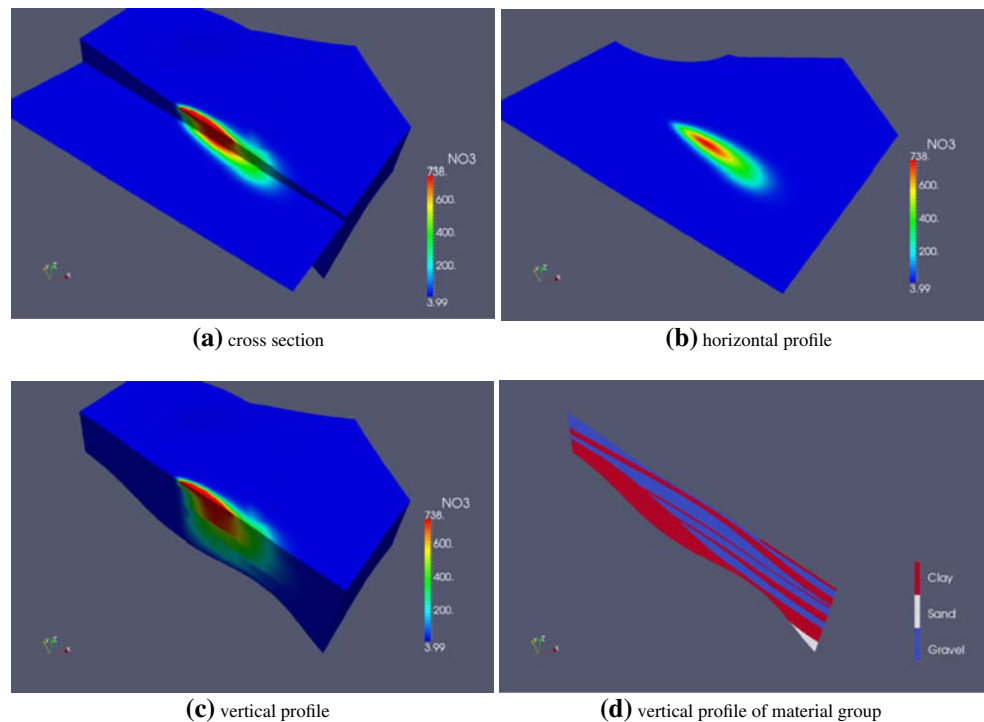
Groundwater that contains dissolved chemicals can be removed from the aquifer so that the contaminated water

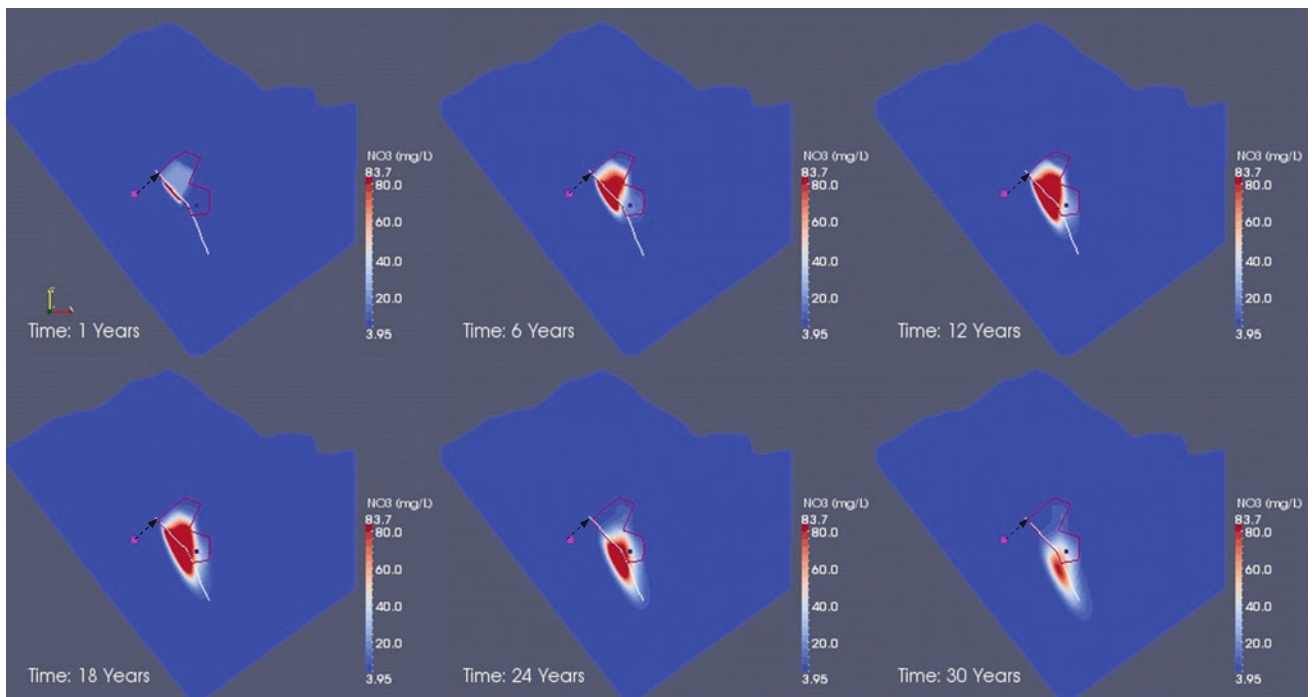
can be treated at the surface with the conventional methods of wastewater treatment. To capture a plume of contaminated groundwater, it is necessary to have one or more pumping-wells located down-gradient from the source area. The area contributing flow to that particular well is known as the capture zone. The contaminants within the capture zone will flow to the well once the pumping starts. A method for determining the optimum number of extraction wells, their locations and the rate at which each well should be pumped has been developed by Javandel and Tsang (1985), in which a series of capture zone type curves (Fig. 11) are used as tools for the design of aquifer clean-up projects.

To identify the nitrate pollution plume in the vicinity area of well #346, an in-depth groundwater-quality investigation was carried out by BHC in October, 2010. The water samples from additional 16 wells focused on this site (see location in Fig. 10b) were analyzed in the laboratory. With these measurements, the nitrate plume contour lines interpolated with an inverse distance-weighted method are shown in Fig. 10a.

Based on the steady-state groundwater flow model, the Darcy’s flow velocity through well #346 is in the direction of 60° counter-clockwise to the positive *x*-axis direction. The regional velocity of  $6.0 \times 10^{-7}$  m/s can be estimated by Darcy’s law. In the case of Fig. 11, the parameter  $Q/BU$  is 2,000 m, where  $Q$  [ $L^3/T$ ] is the well pumping rate,  $B$  [L] is the aquifer thickness and  $U$  [L/T] is the Darcy velocity. According to the borehole log in this site, the average aquifer thickness is 50 m. Hence, based on the

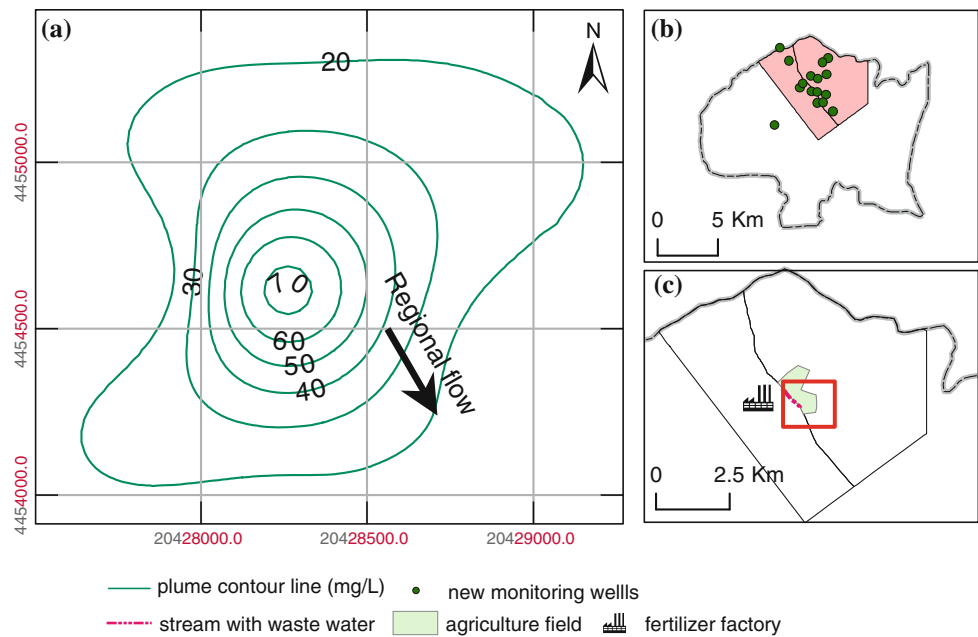
**Fig. 8** Simulation results of the contamination plume after 30 years (unit: mg/l)





**Fig. 9** The nitrate plume evolution under the scenario of irrigation with wastewater

**Fig. 10** **a** The nitrate plume contour map. **b** The groundwater quality-monitoring wells around well #346. **c** The location of the pollution sources for the 3-D mass transport model

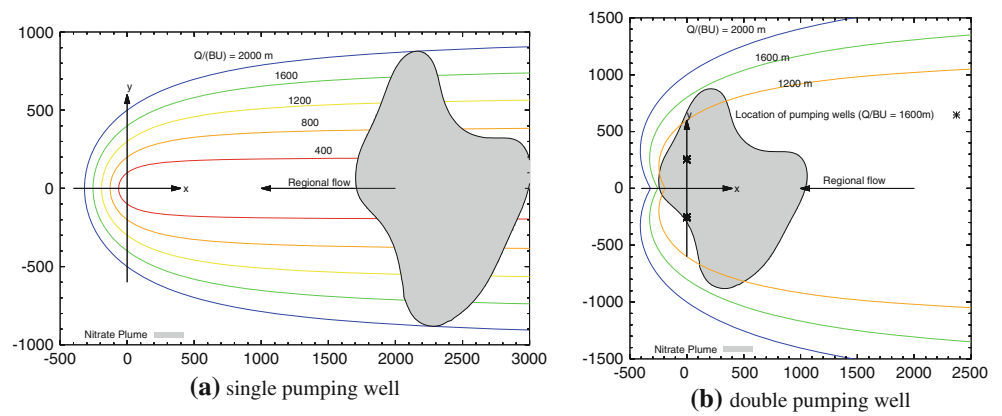


above relationship of  $Q$ ,  $B$  and  $U$ , the pumping rate for one well is equal to  $0.06 \text{ m}^3/\text{s}$ . Other results, including two pumping well scenario, are listed in Table 5, and the location coordinates in Table 5 mean the transformations of well #346 in the local coordinate system of Fig. 11a, b. The results in Table 5 show that pumping with a two wells

will take away the contaminant plume in a shorter time period but will induce much deeper drawdown.

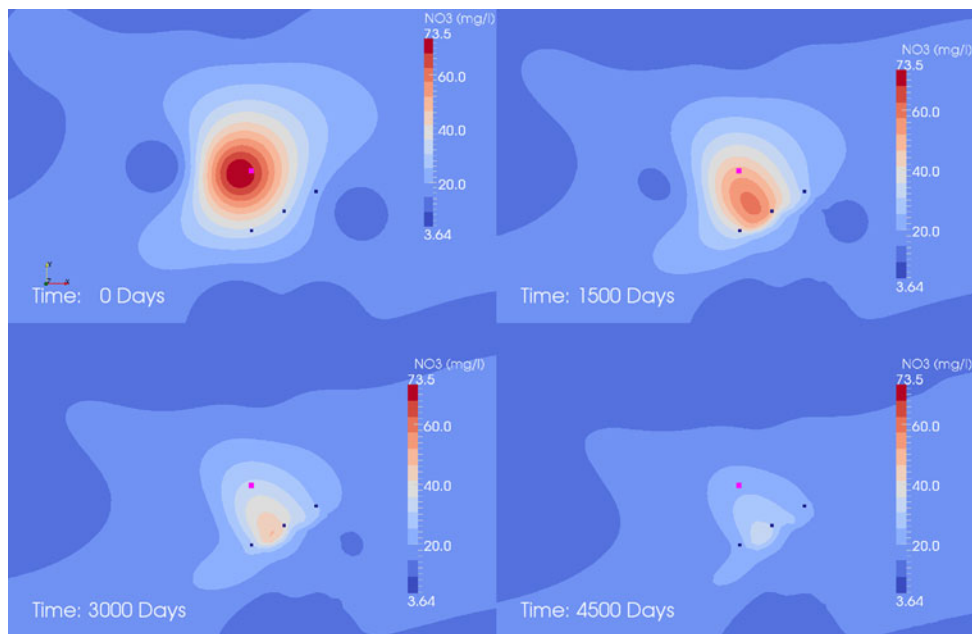
The pumping rate in Table 5 is an analytical solution for the 2-D case and can be used as a primary estimated value of the pumping rate for the 3-D case. With the estimated pumping rates, a two-wells setup is initially employed in

**Fig. 11** Maps of nitrate plume combined with type curves in the regional flow direction



**Table 5** Characteristics of the clean-up scenarios for one or two pumping wells

Number of pumping wells	Location of well #346	Pumping rate at each well (m <sup>3</sup> /s)	Drawdown after 360 days (m)
1	(2300, 140)	6.0e−2	3.96
2	(350, 140)	4.8e−2	4.34



**Fig. 12** Simulation results of the contamination plume evolution after the pumping activities start

the 3-D model. As a result, these two wells can not capture the entire plume even with an elevated pumping rate. After several try-tests, three pumping wells are installed in the downstream direction of the regional flow in the Nankou site. The coordinates of the wells are (20428297.75, 4454246.90), (20428515.74, 4454369.928) and (20428733.73, 445449 2.95) respectively in the Pulkovo\_1942 transverse Mercator projected coordinate system. These three wells are

equally distanced with an interval of 250.3 m. The pumping rate of each well is 32 m<sup>3</sup>/m · d. After 1 year, the nitrate concentration in well #346 goes down to 68 mg/l from the initial concentration of 72.9 mg/l, and it will be lower than the limitation value (20 mg/l) after 5,400 days extraction. Figure 12 shows the nitrate plume changing on different days after pumping activities start.

## Data visualization

Geoscientists are faced with diverse data sets ranging in spatial scales from micrometers to thousands of kilometers and varying on time scales from milliseconds to millions of years. Typically, these observations and monitorings, or the results of numerical simulations, are 3-D gridded data sets, e.g., seismic tomography images of the Earth's interior, finite-element models of mantle convection (Wang et al. 2007), modeling geological structures (Zehner 2006; Wycisk et al. 2009), complex groundwater systems (Beinhorn et al. 2005; Wu et al. 2011), and designing nuclear waste repositories (Kalbacher et al. 2005; Rutqvist et al. 2008; Wang et al. 2011). The use of supercomputers makes scientific visualization indispensable for the analysis of high-resolution numerical models and of uncertainties in geoscience models (Zehner et al. 2010). The scientific "market" for visual data exploration is increasing as more and more visualization facilities become available to environmental research, which encourages the development of special software tools specific to the visualization of geoscientific data (Billen et al. 2008). 3-D virtual reality studies are also very well suited for educational purposes and have already been implemented in several teaching courses in hydrogeology and geo-technics (Rink et al. 2011).

Within the context of the presentation of complex hydrogeological structures and results of the Nankou project to stakeholders and decision makers of the Beijing district, 3-D visualization techniques have been used to provide a better understanding of the involved problems, data and simulation results. To enable scientists to visually examine data sets, the Visualization Toolkit (VTK) is used. It provides several established visualization techniques such as contouring, streamlines and glyphs. Figure 13 shows the nitrate concentration as colored iso-surfaces



**Fig. 13** Streamlines captured by the triple pumping wells and the groundwater flow velocity shown in a virtual 3-D environment

(contouring). In addition, streamlines originating at each pumping well and arrows (glyphs) show the velocity field. The data set is not only static but also contains all time steps of the simulation result, and can therefore be shown in a dynamic animation. It is also possible to view the data visualization on a large stereoscopic screen in a visualization laboratory for collaborative work-group sessions with people from different backgrounds or to present it with mobile equipment for educational purposes and on-site demonstration to the stakeholders.

## Conclusions and outlook

In this work, a modeling framework is developed to reproduce the nitrate transport process in the aquifer at the Nankou site under different pollution sources, i.e., fertilizer factory, river with wastewater and agriculture fields, which presents a better understanding of the nitrate transport in the local aquifer. In addition, a pumping clean-up scenario is designed based on the current nitrate concentration distribution. The pumping rate and the well location are first estimated with the 2-D analytical solutions of the type curves method. Then the 3-D numerical model is used to calculate the nitrate concentration changes after the pumping activities start. The following conclusions can be drawn based on the outcome of this work:

1. The local intensive discharge of high nitrate concentration wastewater still impacts the groundwater quality even though it is 20 years after the pollution source was removed.
2. In the 2-D case, the uncertainty distribution of heterogeneous hydraulic conductivity has an influence on the groundwater flow pattern and consequently to contaminant transport. The best fit between the calculated hydraulic heads and the observed values can be achieved by the calibration of lateral recharge fluxes.
3. The application of 3-D visualization technology in the Nankou project gives a more vivid environment for the discussion between scientists and stakeholders. The complicated hydrogeological structures can be integrated with the vector results (e.g., groundwater velocity field and mass flux) as well as the dynamic animation of the nitrate concentration changes in this case.
4. The pumping clean-up method is a feasible strategy for the nitrate-contaminated groundwater remediation. The triple pumping-wells setup in the study area has been proposed to the stakeholders as scientific support for the remediation strategy decision-making. As for a water resource scarcity area, the pumped water will be used for farmland or ornamental plant garden irrigation

in the vicinity. The optimization with the total pumping rate and clean-up time as objectives for multi-pumping wells will be continued in future research along with new available data from the stakeholders of the Nankou site. Based on extended data sets, the research will be continued concerning the description of in-situ denitrification processes and uncertainty assessment for contaminant transport in the Nankou site. Future work will be conducted in close cooperation with BHC and the stakeholders as well.

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## References

- Anderson EI, Mesa E (2006) The effects of vertical barrier walls on the hydraulic control of contaminated groundwater. *Adv Water Resour* 29(1):89–98
- Baú DA, Mayer AS (2008) Optimal design of pump-and-treat systems under uncertain hydraulic conductivity and plume distribution. *J Contam Hydrol* 100(1–2):30–46
- Bauer S, Beyer C, Kolditz O (2006) Assessing measurement uncertainty of first-order degradation rates in heterogeneous aquifers. *Water Resour Res* 42(W01420):227–244
- Bear J (1972) *Dynamics of Fluids in Porous Media*. American Elsevier, New York
- Beinhorn M, Dietrich P, Kolditz O (2005) 3-d numerical evaluation of density effects on tracer tests. *J Contam Hydrol* 81(1–4):89–105
- Beyer C, Bauer S, Kolditz O (2006) Uncertainty assessment of contaminant plume length estimates in heterogeneous aquifers. *J Contam Hydrol* 87(1–2):73–95
- Billen MI, Kreylos O, Hamann B, Jadamec MA, Kellogg LH, Staadt O, Sumner DY (2008) A geoscience perspective on immersive 3d gridded data visualization. *Comput Geosci* 34(9):1056–1072
- Bissinger V, Kolditz O (2008) Helmholtz interdisciplinary graduate school for environmental research (HIGRADE). *GAIA - Ecol Perspectives Sci Soc* 17(1):71–73
- Cheremisinoff NP (1998) Pump-and-treat remediation technology. In: *Groundwater Remediation and Treatment Technologies*, William Andrew Publishing, Westwood, pp 203–258
- Doherty J (2004) *PEST: model independent parameter estimation*, 5th edn. Watermark Numerical Computing, Brisbane, Australia
- Fan AM, Willhite CC, Book SA (1987) Evaluation of the nitrate drinking water standard with reference to infant methemoglobinemia and potential reproductive toxicity. *Regul Toxicol Pharmacol* 7(2):135–148
- Fetter CW (1998) *Contaminant hydrogeology*, 2nd edn. Prentice Hall Publishing Company, Upper Saddle River
- Freeze RA, Cherry JA (1979) *Groundwater*. Prentice Hall Inc., Englewood Cliffs
- Hudak PF (2000) Regional trends in nitrate content of Texas groundwater. *J Hydrol* 228(1–2):37–47
- Hunter WJ (2001) Use of vegetable oil in a pilot-scale denitrifying barrier. *J Contam Hydrol* 53(1–2):119–131
- Javandel I, Tsang C (1985) Capture-zone type curves: A tool for aquifer cleanup. *Ground Water* 24(5):616–625
- Ju X, Kou C, Zhang F, Christie P (2006) Nitrogen balance and groundwater nitrate contamination: Comparison among three intensive cropping systems on the north China plain. *Environ Pollut* 143(1):117–125
- Kalbacher T, Wang W, McDermott C, Kolditz O, Taniguchi T (2005) Development and application of a CAD interface for fractured rock. *Environ Geol* 47:1017–1027
- Kolditz O et al (2012) OpenGeoSys: an open source initiative for numerical simulation of THMC processes in porous media. *Environ Earth Sci*. doi:10.1007/s12665-012-1546-x
- Lan T (2007) A discussion on specific capacity and the transmissivity (in Chinese). *GROUND WATER (China)* 29:43–45
- Lan T, Zhao A, Liu Q (2004) The experimental study on the relationship between hydraulic conductivity and the specific capacity (in Chinese). *GROUND WATER (China)* 26:6–10
- Loxham M, Westrate F (1985) The use of a cement-bentonite cut-off wall to contain possible pollutants from a landfill containing highly polluted dredging spoils. *Eng Geol* 21(3–4):359–365
- Matott LS, Rabideau AJ, Craig JR (2006) Pump-and-treat optimization using analytic element method flow models. *Adv Water Resour* 29(5):760–775
- Pebesma EJ, Wesseling CG (1998) Gstat: a program for geostatistical modelling, prediction and simulation. *Comput Geosci* 24(1):17–31
- Rink K, Kalbacher T, Kolditz O (2011) Visual data management for hydrological analysis. *Environ Earth Sci*. doi:10.1007/s12665-011-1230-6
- Rutqvist J, Barr D, Birkholzer JT, Chijimatsu M, Kolditz O, Liu Q, Oda Y, Wang W, Zhang C (2008) Results from an international simulation study on coupled thermal, hydrological, and mechanical processes near geological nuclear waste repositories. *J Nucl Technol* 163(1):101–109
- Saffigna PG, Keeney DR (1977) Nitrate and chloride in ground water under irrigated agriculture in central Wisconsin. *Ground Water* 15(2):170–177
- Singh B, Sekhon G (1979) Nitrate pollution of groundwater from farm use of nitrogen fertilizers: a review. *Agric Environ* 4(3):207–225
- Strelbel O, Duynisveld W, Boetcher J (1989) Nitrate pollution of groundwater in western Europe. *Agric Ecosyst Environ* 26(3–4):189–214
- Su C, Puls RW (2007) Removal of added nitrate in the single, binary, and ternary systems of cotton burr compost, zerovalent iron, and sediment: implications for groundwater nitrate remediation using permeable reactive barriers. *Chemosphere* 67(8):1653–1662
- Sun F, Shao H, Kalbacher T, Wang W, Yang Z, Huang Z, Kolditz O (2011) Groundwater drawdown at Nankou site of Beijing Plain: model development and calibration. *Environ Earth Sci* 64(5):1323–1333
- Till BA, Weathers LJ, Alvarez PJJ (1998) Fe(0)-supported autotrophic denitrification. *Environ Sci Technol* 32(5):634–639
- Wang D, Shen Z, Zhong Z, Chen L (1998) Effects of nitrogen transformation on hardness increment of groundwater. *Geoscience* 12
- Wang S, Zhang S, Yuen DA (2007) Visualization of downwellings in 3-d spherical mantle convection. *Phys Earth Planet Interiors* 163(1–4):299–304
- Wang W, Rutqvist J, Görke UJ, Birkholzer J, Kolditz O (2011) Non-isothermal flow in low permeable porous media: a comparison of

- unsaturated and two-phase flow approaches. *Environ Earth Sci* 62:1197–1207
- Wu Y, Wang W, Toll M, Alkhoury W, Sauter M, Kolditz O (2011) Development of a 3D groundwater model based on scarce data: the Wadi Kafrein catchment/Jordan. *Environ Earth Sci* 64: 771–785
- Wycisk P, Hubert T, Gossel W, Neumann C (2009) High-resolution 3d spatial modelling of complex geological structures for an environmental risk assessment of abundant mining and industrial megasites. *Comput Geosci* 35(1):165–182
- Zehner B (2006) Interactive exploration of tensor fields in geosciences using volume rendering. *Comput Geosci* 32(1):73–84
- Zehner B, Watanabe N, Kolditz O (2010) Visualization of gridded scalar data with uncertainty in geosciences. *Comput Geosci* 36(10):1268–1275
- Zhang H, Hiscock K (2011) Modelling the effect of forest cover in mitigating nitrate contamination of groundwater: A case study of the sherwood sandstone aquifer in the east midlands, UK. *J Hydrol* 399(3–4):212–225
- Zhang WL, Tian ZX, Zhang N, Li XQ (1996) Nitrate pollution of groundwater in northern china. *Agric Ecosyst Environ* 59(3): 223–231
- Zhao D, Sun B (1979) The gazetteer of Changping county, Beijing. Beijing Publishing Group, Beijing
- Zheng C, Bennett G (2002) Applied contaminant transport modeling. Wiley-Interscience