ORIGINAL ARTICLE

Environmental impact assessment of risk associated with groundwater overdraft remediation in cone of depression, Jining, China

B. T. I. Ong'or · Long-cang Shu · Pei-gui Liu

Abstract In this paper, a simple scenario and probabilistic approach is used to assess the potential groundwater risk due to proposed overdraft remedial actions in cone of depression, Jining City, China. Focusing on the concentrations of Chloride ions (Cl^-) and total hardness (TH), the impact of artificial recharge and reduced pumping on groundwater quality and quantity is analysed by using the three-dimensional finite difference groundwater flow and transport model, Visual MODFLOW, to simulate groundwater flow and transport within the study area based on scenarios, and utilizes SURFER software to map risk levels. Although 5, 10 or 15% reduced pumping with artificial recharge leads to more decrease in Cl^- and TH concentrations than the 25%, less volume increase is achieved for the remediation of land subsidence and other environmental problems in the cone of depression. The Cl^- concentrations in recovered groundwater are within the desired concentration of 200 mg/l; however, TH in some cases are above the maximum permissible limit of 500 mg/l, with an exceedence probability of about 0.67 for recharge and recharge with reduced pumping at 25%. The presence of fractures and hydrogeological complexity greatly determines impacts of remediation, and the 22% reduced pumping with artificial recharge offers an optimum strategy for overdraft remediation in the Jining cone of depression.

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Introduction

Jining city in Shadong province heavily depends on groundwater as its source of water for domestic, industrial and agricultural development. The ever-increasing water demand has led to over abstraction of this precious water resource through a number of drilled wells, resulting in its overdraft with the consequences of land subsidence, formation of cone of depression and groundwater pollution. Despite efforts by the central and local governments to limit the pumping of groundwater and replenish it with surface water since the 1990s, which has slowed the rate of sinking, the total area suffering from surface subsidence is quickly expanding, creating huge economic losses and also posing serious threat to buildings and people's lives. The proposed remedial actions (recharge, reduced pumping, total closure of wells etc.), presents a wide spectrum of health challenges which must be carefully evaluated prior to undertaking the actions, since they are all associated with some level of risk. Reduction in pumping is currently ongoing in selected areas within the cone of depression; however this study uses a probabilistic approach in analysing the possible impacts of reduced pumping and artificial recharge with an aim of assessing the risk associated with them as remedial actions on the groundwater overdraft in the cone of depression in Jining City. First an analytical approach based on scenario development is done and then a comparison of the ratios of simulated concentrations and desired/permissible levels is done and finally, a probabilistic approach for TH at 25% reduced pumping with artificial recharge is carried out.

Environmental risk assessment

Natural systems can never be perfectly known, risks associated with management decisions can be analysed and policies adopted that minimize the risk of undesirable consequences such as contaminating the aquifer or pumping at a rate faster than the desired. Risk exists when there is the possibility of adverse outcome; hence improving decision-making therefore requires looking for ways of improving the quality of the judgment of the decision maker (Fischhoff 1990). However, environmental risk (including groundwater) is not simply risk to the natural environment but also includes ecological risk, human health risk, social, and cultural risk. The different measures of risk are being used for different purpose, from qualitative prioritization and screening to quantitative risk assessment and decision analysis.

Risk assessment is the process of estimating the potential impact of chemical, biological or physical agents on humans, plants, animals and ecology. Risk assessment has been used internationally for several years to assess different activities that impinge on the environment (Anderson et al. 1990); in most cases environmental risk assessment has been limited to one type of risk and a restricted geographical area. The analytic hierarchy processes, scenario analysis, method of specialist investigation are some of the common methods in risk assessments (Ma Rong-yong 2004). These methods can be further grouped into three different risk assessment methodologies and have been widely used: the technical risk assessment (TRA) for environmental risk assessment, which requires making estimates of probability of harm to plant and animal life, and to ecosystem integrity, the decision-analytic approach (DA), where risk is not regarded as an objective property of an object or situation but as a subjective mental construction based on personal beliefs about the occurrence of specific outcomes of an event or action (Harry and Peltu 1985), and the comparative risk assessment (CRA) approach which is a reconciliation of the technical with the judgmental. Risk assessment in groundwater is done on the basis of its suitability for current or realistic future use and the risk that use may pose to human health and/or the environment. This assessment takes into account factors relevant to the environmental value of the groundwater resources such as the proposed and realistic future uses, physiochemical and bioavailability characteristics of the particular contaminant(s) and the distribution of the contaminants.

Despite many groundwater overdraft remediation attempts, uncertainty and risks still loom with some of the emerging issues to be addressed, as the following: can the quality of groundwater be protected or improved? Will the quality of the recovered water be fit for its intended use? Is it economic? Will it work? During the past years it has become widely recognised that remediation of aquifer by pump-and-treat method is extremely difficult within reasonable time frame (Travis and Doty 1990; Stroo et al. 2003; Eberhardt and Grathwohl 2002). The main reasons for the difficulty in achieving aquifer remediation by pump-and-treat method are related to difficulty in describing the spatial heterogeneities for both hydraulic and chemical properties (Sudicky et al. 1985). Other remedial alternatives for contamination are steam dispersion (Hunt et al. 1988a, b), purging by clean water (Bahr 1989) and containment of contamination by hydraulic gradient (Atwood and Gorelick 1985). The most outstanding approach has been artificial groundwater recharge with either imported surface water or rainwater.

Artificial recharge of groundwater offers a unique solution to groundwater problems by not only storing surplus water for future use, augmenting natural recharge, replenishing depleted aquifer but also ameliorate the groundwater overdraft effects (Bouwer 2002). However the quality and amount of recharge water, the quality of ambient groundwater, hydrogeological set up and human activities, the recharge mechanism and potential for groundwater contamination are of great concern. Though the previous study shows that there is a high potential for groundwater storage and artificial recharge in cone of depression in Jining City (Liu 2005), the vulnerability analysis of groundwater to contamination revealed that more than a half of the study area is highly vulnerable to point and non-point contamination (Wu and Shu 2006). The pumping reductions has also been used in many areas with a goal of allowing groundwater levels to recover, enabling affected environmental systems to recover from decades of groundwater-pumping at unsustainable levels, and currently a number of pumps have been switched off completely in the Jining cone of depression. Its worth noting that while groundwater quantity is a result of various natural factors as well as human activities, the quality evolves as a function of the natural hydrogeological environment and human activities, both interact fully and continuously and hence, must be well understood for any meaningful remediation to take place (Mogheir et al. 2005).

In this study, analyses of the possible impacts of reduced-pumping and artificial recharge with an aim of assessing risk to the groundwater resources in terms of both quality and quantity in the cone of depression, Jining city is done. Achieving this entails using Visual MODFLOW (McDonald and Harbaugh 1996) to simulate the flow and contaminant concentrations under different scenarios, estimation of the increased water volume from the water budget analysis, and carrying out risk assessment using concentration ratios and a probabilistic approach where SURFER software is used to map risk level.
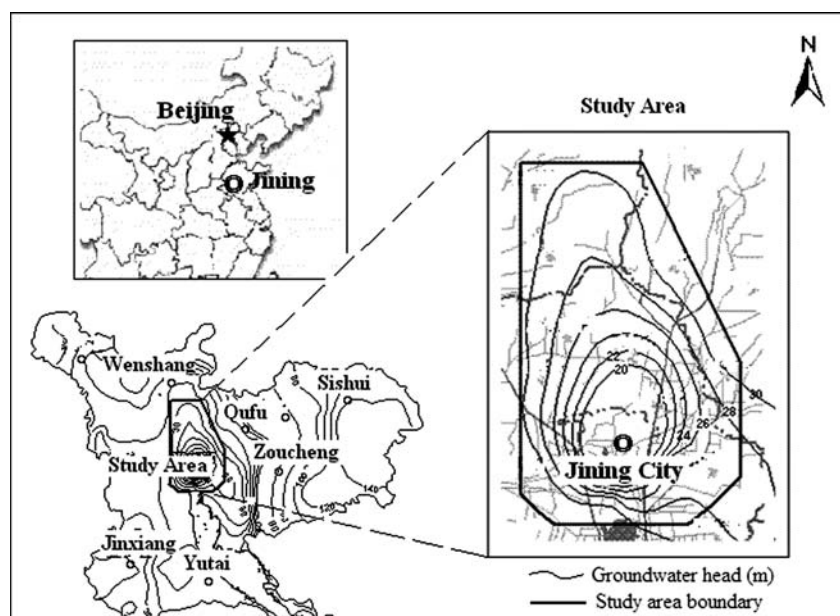
Study area

The study area is located in the eastern part of China (Fig. 1) between latitude 35°08′ to 36°43′ North and longitude 116°26′ to 116°44′ East. It spreads over an area of about 682 km^2, with a population of a bout 0.4 million. It is situated at the joint area of hills and west plains, and connected to the lower reach of Nansi Lake watershed in the south, the flood plains of the Yellow River to north-west, and slightly slopes to the southeast, with a depression at the middle and southern parts. The study area annual average precipitation is about 672.99 mm, most of which is felt in the months of June–September. The spatial distribution of precipitation in the study area is quite evident, with the eastern part experiencing more than the western part. The annual evaporation ranges from 667.78 to 914.34 mm with a mean of 792.8 mm. The area's groundwater is withdrawn through 23 pumping wells, and being part of the Huaihe River watershed, several rivers and artificial water diversion canals drain into the area, the main ones being the Great Canal (Jing-Hang Water Canal) and Guangfu River with maximum discharges of 68.86 m^3/s and 4.00 m^3/s, respectively (Fig. 2).

The average elevation of the study area is about 38 m above mean sea level (amsl, ranging from 35.1 m to 40.4 m, with an average slope of 0.57%. The general topographic characteristic of the study area is plain with slight sloping from northwest to southeast with a slight depression in the middle and southern part. It is located at the joint area of hills, west plains and lower reaches of Nansi Lake watershed in the south and enclosed within a

number of fractures (Fig. 3). The geological set up is based on Tertiary, Upper Jurassic, Perm-Carboniferous, Cambro-Ordovician and Magmatic rocks, however the general soil texture in the study area ranges from low permeable sandy silt in the middle south to the highly permeable coarse sand in the central and northern parts (Fig. 3). The aquifer comprises of alluvial and fluvial layers of Quaternary de-posit, consisting mainly of clay, sandy clay and sand. The city aquifer consist mainly of sand of different sizes from land surface to a depth of about 150 m, while at the cone of depression, the thickness is more than 100 m, mostly consisting of neoteric river alluvial; however, the lake deposit appears only locally. The aquifer consists of both unconfined, an underlying aquitard and confined layers below the aquitard, of thickness ranges of 47–64, 1–15 and 84–120 m, respectively, with an impermeable bottom lay-er. Repeated floods and sedimentations in history form the intermittent loams and clay lenses separating aquifer into frames of 8–12 layers (Fig. 4). The general groundwater flow is from northeast to southwest with a focus at cone of depression. Water depths range from less than 1.5 m in the southwest to over 30 m in the most over drafted portion of the study area, with the annual groundwater table decline rate of 2.36 m/year. The annual water demand (domestic, industrial and agricultural) for the years 1999 and 2005 are 17131.55 × 10^4 m^3 and 22182.7 × 10^4 m^3, respectively; however, the supply for the year 1999 was 11666.55 × 10^4 m^3 (Liu 2005).

The chemical composition and in particular the salinity of the study area is closely related to the geological for-mation and structure. From the front of the sloping plain of the east of the lake to the alluvial plain of the west of

Fig. 1 Location map of Jining City with general groundwater head in the year 2001
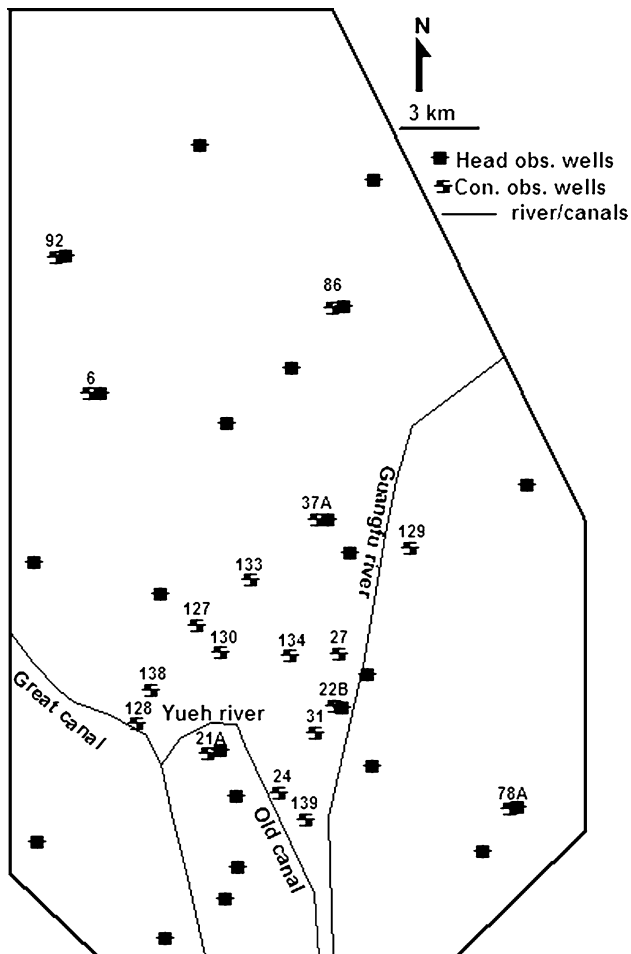
Fig. 2 Drainage and observation wells map of the study area

the lake, and the upper part of the alluvial-proluvial fan, the rate of groundwater flow and amount due to overland flow and runoff changes from mild to low culminating into high salinity and increased total dissolved salts (TDS). The chemical composition of the groundwater in Jining aquifer varies greatly from simple composition of HCO_3^- being lower than 500 mg/l, increasing to 1,000 mg/l in the banks of Great canal (chemical composition being transformed from HCO_3^-–SO_4^{2-} to HCO_3^-–Cl^-). The presence of Palaeozoic stratum, which seems to reduce the speed of groundwater interflow sharply increases salinity to about 1,500 mg/l, with a subsequent alteration of the chemical composition of the groundwater. To the west of the Great Canal and near the Yellow river, the groundwater salinity (composition mainly of HCO_3^-) is lower than 500 mg/l in some areas. It is worth noting that in the mining, industrial and agricultural areas, as well as in settlement areas, groundwater pollution is quite evident, and the extent depends on the severity of these activities and population, with Jining city-centre being a sorry case. Agriculture remains the dominant economic activity in the

peri-urban areas with coal mining in some parts in the northeast.

Methodology and procedure

Risk assessment as defined in this study is fundamentally an attempt to quantify the possible overdraft remediation consequences to both human health and environment, in terms of the quantity and quality of recovered groundwater. The approach adopted is a combination of scenario techniques and probabilistic approach. The two solutes of immediate concern are Cl^- and total hardness (TH). The Cl^- concentrations ranges from about 75.97 to 163.45 mg/l while that of TH ranges from 357.93 to 657.69 mg/l in the cone of depression. While the Cl^- concentrations are within the WHO most desirable limits of 200 mg/l, the TH is mostly above the WHO maximum allowable limits of 500 mg/l (WHO 1971, 1983).

Artificial recharge is achieved by modifying the hydraulic conductivity (K) value of the river bed material to 20 m/day for Old Canal, Yueh River and the Great Canal (Jing-Hang Canal) as an imitator of spreading method, and also through infiltration and injection wells in and around the cone of depression in Jining City at a recharge rate of 150 and 2,000 m³/day, respectively. The distance between recharge 'facilities' and observation wells are set to be at least 50–100 m (Asano and Cotruvo 2004; Fox P et al. 2001). A recharge water of Cl^- and TH concentrations of 150 and 200 mg/l, respectively, (to conform to the Grade 2 groundwater quality standards GB/T14848–93) was used for recharge purpose.
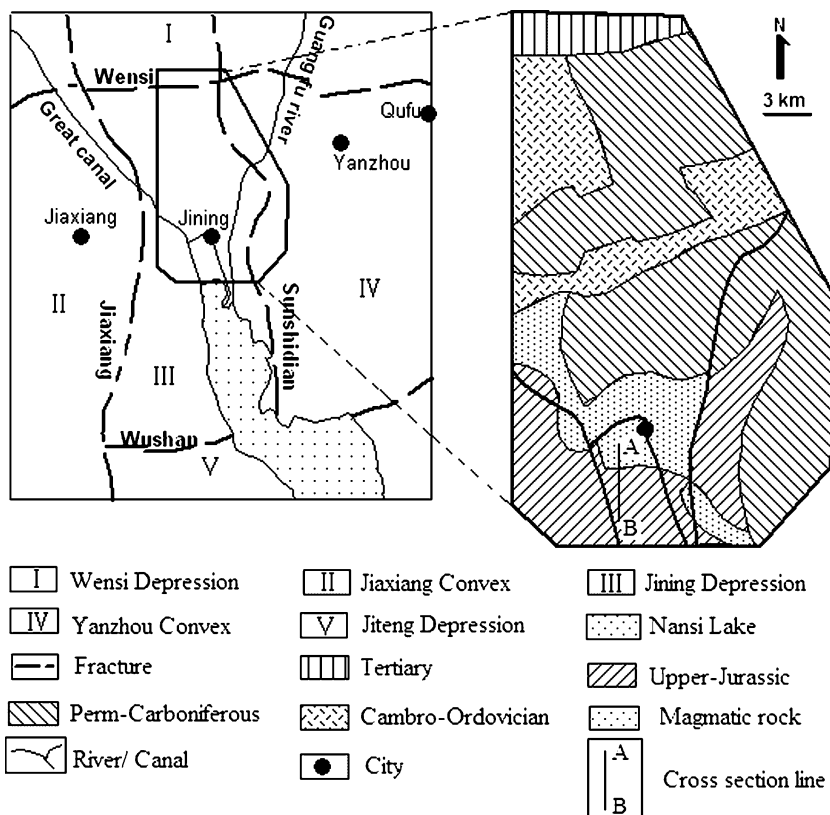
Scenario formulation

By using the scenario risk assessment techniques, the nine scenarios formulated and evaluated focusing on the most overdrafted areas within the study area, are:

1. Reduced pumping rate for the 35 pumps within the cone of depression by 5, 10, 15, and 25% without carrying out artificial recharge.
2. Reduced pumping rate for the 35 pumps within the cone of depression by 5, 10, 15, 25 and 50% with artificial recharge.

The visual MODFLOW was initially calibrated and verified upon getting the best-of–fit between observed field data (1991–2001) with the simulated ones. The general, three-dimensional partial finite differential equation for a constant density transient groundwater flow and that of transport in a heterogeneous and anisotropic medium (provided the principle axes of hydraulic conductivity are aligned with the coordinate directions), for a confined or

Fig. 3 General geological map of Jining

I Wensi Depression   II Jiaxiang Convex   III Jining Depression

IV Yanzhou Convex   V Jiteng Depression   Nansi Lake

Fracture   Tertiary   Upper-Jurassic

Perm-Carboniferous   Cambro-Ordovician   Magmatic rock

River/ Canal   City   Cross section line

unconfined aquifer, is expressed as (Bear 1979; Charles 2002; Freez and Cherry 1979; Todd and Larry 2005).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)$$
$$+ N(x,y,x,t) = S_s\frac{\partial h}{\partial t} \tag{1}$$

where K_{xx}, K_{yy}, and K_{zz} are the hydraulic conductivities along the X, Y, and Z coordinate axes parallel to the major axes of hydraulic conductivities [L^2T], h is the hydraulic head [L], S_s is the specific storage of the porous medium, N is the volumetric flux per unit volume representing sources and/or sinks of water; and t is time. While the general three-dimensional equation for non-reactive solute transport assuming constant porosity and macro-dispersiveness in time and space is given by:

$$\frac{\partial}{\partial x}\left(D_{xx}\frac{\partial c}{\partial x} + D_{xy}\frac{\partial c}{\partial y} + D_{xz}\frac{\partial c}{\partial z}\right)$$
$$+ \frac{\partial}{\partial y}\left(D_{yx}\frac{\partial c}{\partial x} + D_{yy}\frac{\partial c}{\partial y} + D_{yz}\frac{\partial c}{\partial z}\right)$$
$$+ \frac{\partial}{\partial z}\left(D_{zx}\frac{\partial c}{\partial x} + D_{zy}\frac{\partial c}{\partial y} + D_{zz}\frac{\partial c}{\partial z}\right)$$
$$- \left[\frac{\partial}{\partial x}(V_x c) + \frac{\partial}{\partial y}(V_y c) + \frac{\partial}{\partial z}(V_z c)\right] = \frac{\partial c}{\partial t} \tag{2}$$

where, x, y, and z are Cartesian coordinates aligned along the major axes of hydrodynamic dispersion coefficients D_{xx}, D_{yy}, D_{zz} (L^2/T); c is the concentration of contaminants dissolved in groundwater (M/L^3); V_x, V_y, and V_z are the seepage velocities in X, Y, and Z directions (L/T).

Using the sink/source package in Eq. 1 to represent pumping and or artificial recharge, the solute transport

Fig. 4 A simple geological profile along the section *A–B* in Fig.3 within the cone of depression
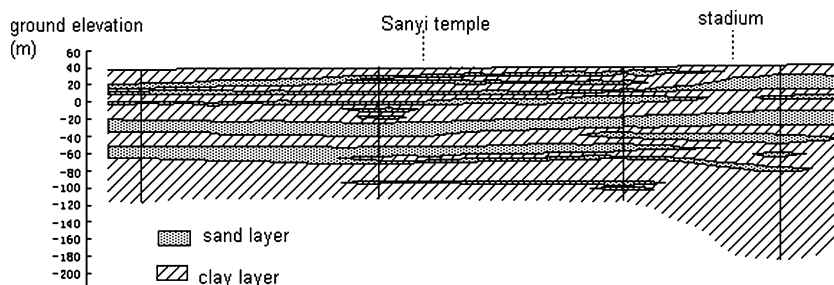
equation 2, is solved by the MT3D (Zheng 1993) package in Visual MODFLOW to determine the concentrations 'c' in recovered water under different scenarios in the observation wells (Fig. 2), and the water mass balance were determined.

Simple probabilistic risk assessment

First an attempt is made to carry out groundwater risk analysis (RA) based on the ratios of concentrations of Cl^- and TH in recovered water to that of desired limit (200 mg/l) and maximum permissible limit (500 mg/l) for Cl^- and TH, respectively. The methodology narrows down to recharge only and 25% reduced pumping with artificial recharge. In this case, risk (RA) can be described as:

$$RA = \sum_{i=1}^{n} \left(Cl_i^- \Big/ Cl_{desi}^- + TH_i^- \Big/ TH_{max}^- \right) \quad (3)$$

where i is the observation well number, n is the number of observation wells, Cl_i^- is the groundwater chloride concentration in the ith observation well, Cl_{desi}^- is the desired chloride concentration, TH_i^- is the total hardness in the ith observation well, TH_{max}^- is the maximum permissible total hardness. The SURFER software is used for creation and overlay of these ratios and is aimed at assessing the risks due to both recharge and with reduced pumping. The 1096-day-data were used for this process.

The probabilistic approach to risk analysis as used by geostatisticians to characterize the spatial and temporal variability provides reasonable and equitable risk acceptability criterion (Davis 1982; Sen 1999; Daniels et al. 2000; Bedford and Cooke 2001; Anderson and Destouni 2001). Risk assessment from probabilistic point of view can be defined as the process of estimating the possibility that a particular event may occur under a given set of circumstances (Finizio and Villa 2002). Mathematically, probabilistic risk analysis is defined as a frequency of occurrence of the harmful event and the severity of the event, where the frequency is a property of the population probability (Bedford and Cooke 2001). It is worth noting that probabilistic methods simplify the risk analysis procedure, but do not replace risk analysis by probability analysis. In this study, risk R, is defined as the probability of a variable, X, to be greater than the maximum permissible, X_{mp}, at least once over the time, T, of consideration. If the sequence of future likely occurrence of X is X_1, X_2, X_3 ...X_n, then the joint probability of non-occurrence is defined as (Daniels et al. 2000):

$$P(N) = P\left(X \leq X_{mp} = P\left(X_1 \leq X_{mp}, X_2 \leq X_{mp}, ..., X_n \leq X_{mp}\right)\right) \quad (4)$$

Then the simple risk is defined as:

$$R = 1 - P(N) = 1 - P\left(X \leq X_{mp}\right) = P(X_1 \leq X_{mp}, X_2 \leq X_{mp}, ...X_n \leq X_{mp})) \quad (5)$$

The determination of the frequency of critical level exceedance is a core element in probabilistic risk assessment, and it is related to the return period, T. The return period and recurrence interval are used interchangeable to mean the average interval of time over which X will be equalled or exceeded (Ray et al. 1982). The return period and probability of exceedance are reciprocals, i.e.

$$p = \frac{1}{T} = P\left(X \geq X_{mp}\right) \quad (6)$$

where p is the probability of exceedance, which can also be expressed in terms of the probability distribution function (PDF) of X as:

$$p = \int_{X_{mp}}^{\infty} f(X) dx \quad (7)$$

Since the Cl^- concentrations in recovered water for both the recharge-only scenario and 25% reduced pumping with recharge are within the WHO (1971, 1983) desired concentration of 200 mg/l, the risk estimation is only done for TH. The choice of probability distribution can have a profound effect on the risk estimation, especially in lower concentrations. The distribution of ambient concentrations is well described in many studies, and it has been established that ambient concentrations of most parameters follow lognormal distribution. The hardness distribution considered in this analysis was taken to follow normal distribution for all the 18 observation points following their Histogram analysis and previous studies elsewhere (Vladimir et al. 2001).

By estimating the mean, μ, and standard deviation, σ, of TH concentrations, the normal distribution with a mean 0, and variance 1 has a PDF of $f(X)$ estimated as (Frederick 1987):

$$f(X) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-u^2/2} du \quad (0 \leq x < \infty) \quad (8)$$

The cumulative PDF for X, in this case TH shows the probability of exceeding allowable limit, p, hence risk calculation. For each and every observation well, the probability, p, is calculated after estimating the mean, μ, standard deviation, σ, and carrying out standardization. The SURFER software is then used for mapping risk values through the Kriging method. Though TH is treated as normally distributed, a plotting position, P_p, is fitted in here for further risk assessment in the city center. The plotting

position normally used for either Weibull or log-normal distribution is described by (Sen 1999).

$$P_p = \frac{m}{n+1} \quad (9)$$

where n is the number of data, and m is the rank of the data in order of the magnitude, the largest having $m = 1$.

Results and discussion

Impact of artificial recharge and reduced pumping on water quantity

Artificial recharge increases both the amount of water and water level in the aquifer by about 3417.69×10^4 m^3/year (34.44% increment) and 6.50 m/year, respectively, which is quite substantial and can alter the bad effects of overdraft. On the other hand, the increase in water level and amount due to reduced pumping and reduced pumping with artificial recharge depends on the % reduction in pumping (Table 1). A reduction in pumping not only increases the amount of water in the aquifer storage but also reduces the supply hence a deficit in supply (Table 1). In all cases of reduced pumping without artificial recharge (5, 10, 15 and 25%), the water level increase rate is less than 2.36 m/year; however, in combination with artificial recharge, more than 2.36 m/year groundwater level increase rate is observed, hence addressing the environmental restoration issue with significant water volume stored within the given time limit; in both cases there is no significant difference in increased volume stored for reduced pumping above 15%. The supplies are estimated from the 2005 supply amount, which is assumed to be the same as that of 1999 i.e. 11666.55×10^4 m^3/year (Liu 2005), and are the 2005 supply less amount increased in aquifer volume due to reduction in pumping. Though the 50% reduced pumping with artificial recharge leads to an increase of water volume of $6,460 \times 10^4$ m^3/year, it is unacceptable since there is need for domestic, industrial and agricultural use. A combination of

Table 1 Volume increase due to reduced pumping (R_p), reduced pumping with recharge ($R_p R_{ch}$), supply and deficit

Percentage of reduction in pumping	Increase in volume (R_p) 10^4 m^3/year	Increase in volume ($R_p R_{ch}$) 10^4 m^3/year	Supply 10^4 m^3/year	Deficit 10^4 m^3/year
5	400	3904.7	11266.55	10916.15
10	840	4181.79	10826.55	11356.15
15	1194.91	4612.53	10471.64	11711.06
25	1381.21	4798.19	10285.34	11897.36

reduced pumping with artificial recharge, which embraces not only the quantity but also quality for both environmental restoration and human health, is desired.

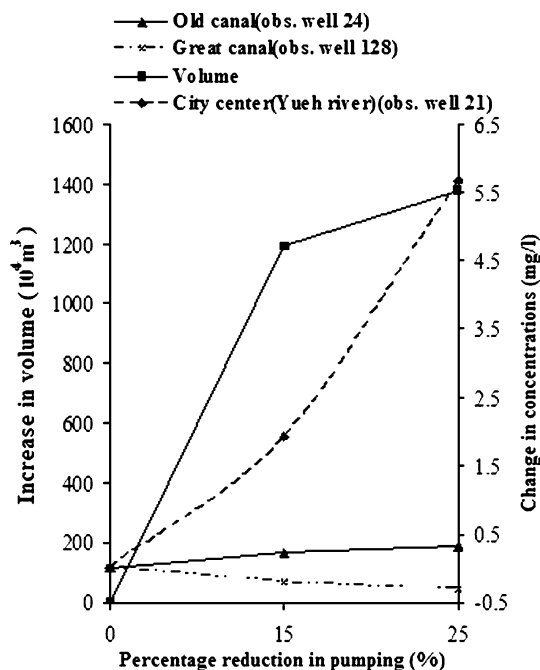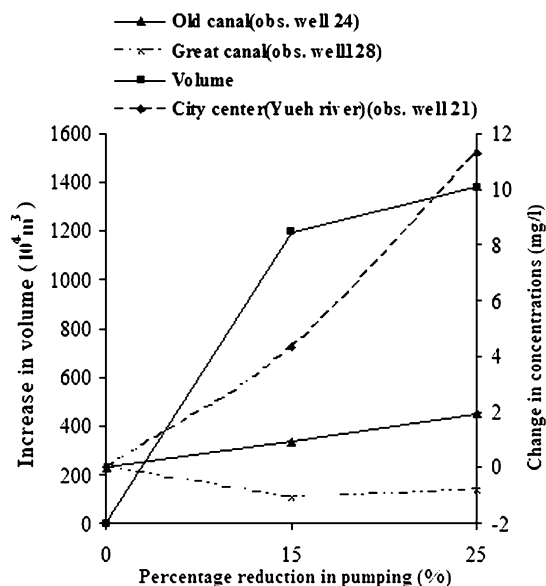### Impact of artificial recharge and reduced pumping on water quality

Chloride ions (Cl$^-$)

A reduction in pumping rates by 15 and 25% without artificial recharge leads to an increase in Cl$^-$ concentration by about 1.93 and 5.68 mg/l, respectively, a difference of 3.75 mg/l, while a reduction by 25 and 50% with artificial recharge leads to a reduction of Cl$^-$ content by 4.28 and 3.05 mg/l, respectively, a difference of 1.23 mg/l (Fig. 5). This implies that, at this local scale within the vicinity of cone of depression, the negative impact of reduced pumping alone on Cl$^-$ concentrations is more at higher reduced rates than at lower reduced rates, whereas when combined with artificial recharge it is vice-versa. Moreover, once a reduction in pumping has taken place, the impact of artificial recharge is more than without i.e. while the differences in Cl$^-$ concentrations between 25% reduced pumping and that of 25% reduced pumping with artificial recharge is about 9.96 mg/l, the difference in Cl$^-$ concentrations recharge-only scenario and the initial situation before artificial recharge is 4.01 mg/l. In general, a reduction in pumping without recharge leads to an increase in Cl$^-$ concentration within the cone of depression. The cone of depression is characterized by Neoteric river alluvial deposits, sandy, sandy clay and sandy grit aquifer formation, and the water is abstracted from deep aquifer (confined). On a spatial scale, the impact of reduction in pumping is felt in the entire study domain with more Cl$^-$ concentrations increase in the city center.

Total hardness (TH)

A reduction in pumping rates by 15 and 25% without artificial recharge leads to an increase in TH concentration by about 4.35 and 11.30 mg/l, respectively, a difference of 6.98 mg/l, while a reduction by 25 and 50% with artificial recharge leads to a decrease in TH concentration by 12.23 and 23.35 mg/l, respectively, a difference of 11.12 mg/l. This implies that the impact of reduced pumping alone on TH concentrations is much at higher reduced rates than at lower reduced rates, whereas when combined with artificial recharge it is vice-versa. Once reduced pumping has taken place, the impact of artificial recharge on TH concentrations is almost the same as that of artificial recharge without reduced pumping i.e. the TH concentration difference between 25% reduced pumping and that of 25%

Fig. 5 Comparison of change in volume, change in Cl⁻ concentrations and percentage reduction in pumping in overdrafted area

Fig. 6 Comparison of change in volume, change TH concentrations and percentage reduction in pumping in overdrafted area

reduced pumping with artificial recharge is 277.84 mg/l, while the difference of TH between recharge-only scenario and the initial situation before artificial recharge is 278.77 mg/l within the cone of depression. On a spatial scale, the impact of a reduction of pumping by 15% and 25% is mostly felt in the southern, southwest and in the cone of depression in the study domain where there is an increase in TH (Fig. 6). However, the 25% reduction in pumping and artificial recharges impacts significantly in the entire study domain with a decrease in TH, the greatest being at the cone of depression, south and southwest sections compared to the rest of the study area.

In general, while the Cl⁻ concentrations is within the most desired limit of WHO international standard of 200 mg/l, the TH concentration varies significantly, and surpasses the maximum allowable limit of 500 mg/l in some cases, especially in the cone of depression. The decrease in Cl⁻ concentrations and TH in south western section (West of Great canal) due to reduced pumping with artificial recharge can be attributed to the existence of Jiaxiang fracture, where the initially precipitated minerals in its wall are dissolved, modifying its permeability by widening the pores/fractures allowing more water of lower Cl⁻ concentrations and TH to move towards this section diluting it, while to the east of city center and Guangfu river, the Shunshidian fracture plays a similar role. Moreover at 22% reduced pumping with artificial recharge, the change in Cl⁻ concentration is the same for both reduced pumping only and reduced pumping with artificial

recharge, and seems to be the better risk option as it offers an optimum (trade off) in terms of both quantity and quality combined for the Jining city-centre in the cone of depression (Fig. 7). At this point, the volume increased stabilized at about 4,600 × 10⁴ m³. It is worth noting that even though the 5, 10 or even 15% reduced pumping with artificial recharge will lead to a less increase in Cl⁻ concentrations than the 25% within the cone of depression, the issue of environmental restoration e.g. reversing the land subsidence can only be achieved by creating more water pressure through addition of water.

Simple probabilistic risk assessment

A comparison of risk levels due to recharge and at 25% reduced pumping with artificial recharge using risk
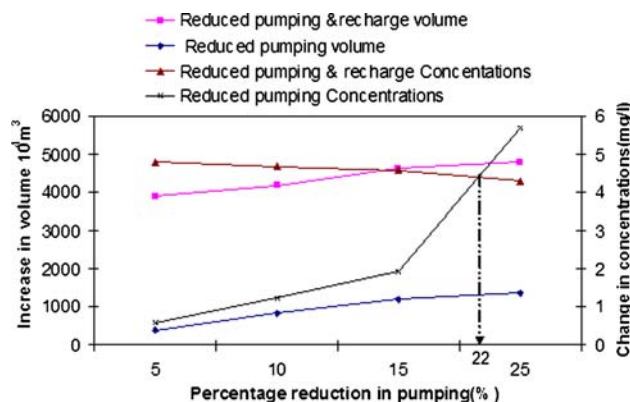
Fig. 7 Comparison of change in volume, change in Cl⁻ concentrations, percentage reduction in pumping and percentage reduction in pumping with artificial recharge in cone of depression

assessment methodology based on ratios (RA) indicates that reduced pumping with artificial recharge leads to a spatial higher risk especially within the cone of depression, and south-western parts (Figs. 8, 9). This can be attributed to TH concentrations since, the Cl⁻ concentrations are within the most desired WHO limits and do not vary significantly.

The probabilistic spatial risk levels due to TH are shown in Figs. 10 and 11. Though there seems to be no significant difference between the risks under the two analysed scenarios, a closer look indicates that the risk due to TH concentrations reduces when reduced pumping is combined with artificial recharge. About 17 and 5.6% of the concentration observation wells (Ob) indicate a probability of more than 0.2 and 0.5 of exceeding the TH WHO maximum allowable concentration of 500 mg/l for recharge-only scenario. However, for recharge and reduced pumping, only about 11 and 5.6% of the Ob wells indicate a probability of more than 0.2 and 0.5, respectively of exceeding the TH WHO maximum allowable concentration of 500 mg/l. The 5.6% of the wells with more than 0.5 probability of exceeding the TH maximum allowable concentration of 500 mg/l seems to be from the vicinity of Jining city centre. Figs. 12, 13.

Using concentration observation well no. 21 which lies within the city center, the statistical analysis of probabilistic risk assessment through an attempt of plotting positions shows that there is no major significant difference between the probability of exceeding the TH WHO maximum allowable concentration of 500 mg/l for recharge-only scenario and that for recharge with reduced pumping of 25%, i.e. in both cases, the probability of exceeding the TH maximum allowable limit is about 0.67; however, based on the average values (546.96 mg/l and 545.16 mg/l for recharge only and recharge with reduced pumping respectively), and given the uncertainties and risks associated with the estimation of these probabilities, one can accept the almost 50% risk as for recharge and reduced pumping scenario.

Conclusion

Artificial recharge of aquifer by spreading or injection techniques coupled with reduced pumping offers a relatively inexpensive overdraft remedial option. However, in an attempt to integrate the artificial recharge potentiality with the groundwater contamination vulnerability, it is
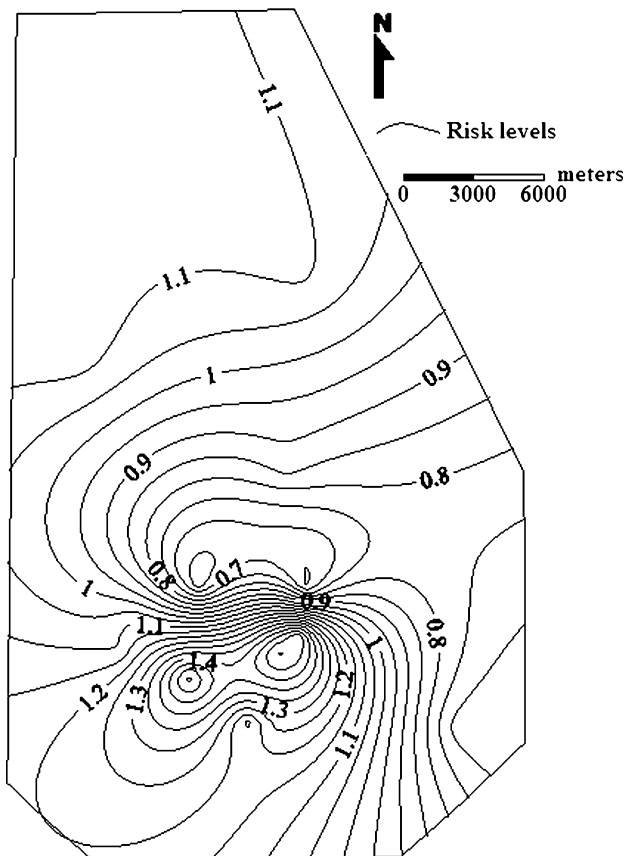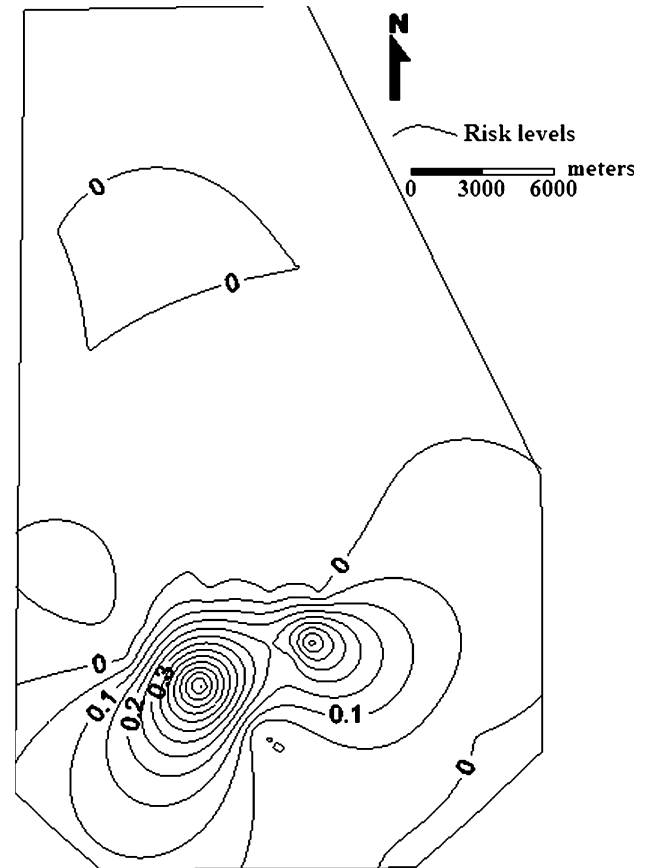

Fig. 8 Risk maps for recharge-only scenario
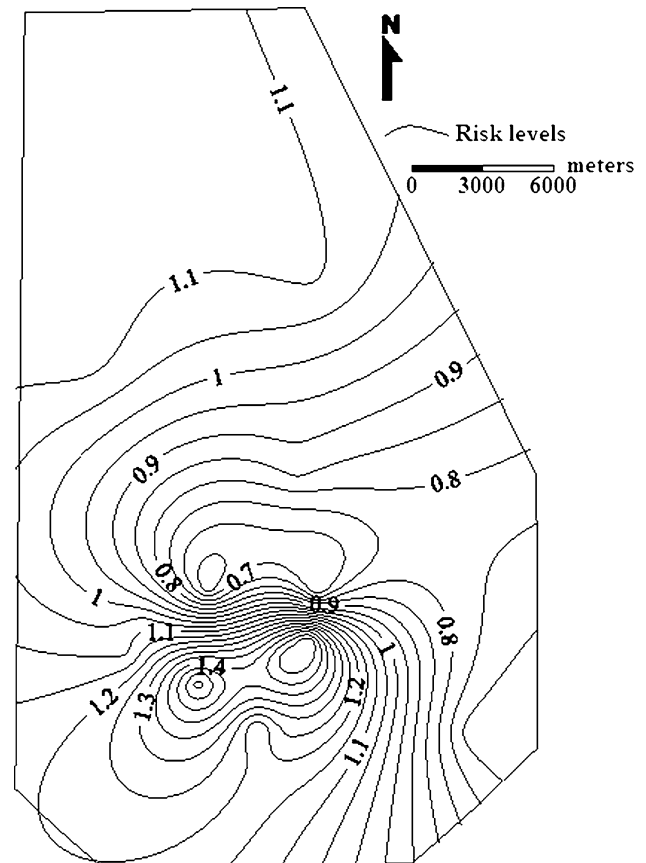
**Fig. 9** Risk maps for recharge with 25% reduced pumping scenario
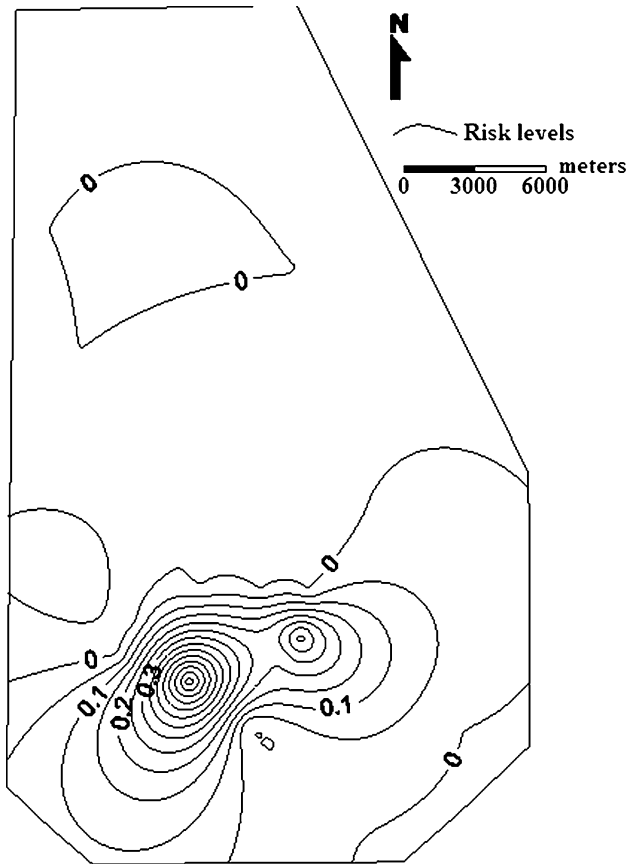
Fig. 10 Risk maps for TH for recharge-only scenario

Fig. 11 Risk maps for TH reduced pumping at 25% with recharge scenario

important to take into account the geo-environment factors like topography, geology, hydrogeology, and even land use as well as the water demand for human use when opting for the overdraft remediation option. In this study, the environmental impacts of artificial recharge and reduced pumping as groundwater overdraft remediation options in Jining city cone of depression was investigated by using groundwater flow and solute model (Cl⁻ and TH), and employing a quantitative and qualitative methodology to asses the associated risk. The recovered groundwater solute concentrations, increased concentrations and increased volume were used.

Though reduced pumping and artificial recharge increases the amount of groundwater generally, they respectively lead to increase and decrease in Cl⁻ and TH concentrations. However, recharge and at 25% reduced pumping with recharge, the Cl⁻ concentrations is within the desired WHO limit, and TH-permissible WHO limits is exceeded in some cases, hence the higher risk levels in reduced pumping with artificial recharge as indicated by ratio methodology (RA) is due to TH. The probabilistic approach tries to incorporate the risk concepts in
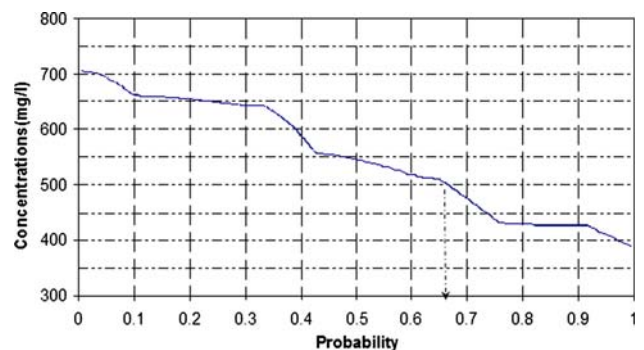
Fig. 12 Exceedance probabilities for observation well no. 21 under recharge-only scenario

groundwater overdraft remediation and management. By using the probability of exceeding set limits in conjunction with opinions of experts, it is possible to arrive at a reasonable decision for an aquifer management. Given the uncertainties and risks associated with the estimation of these probabilities, the probability of exceeding the permissible limit of TH for recharge and recharge with 25%
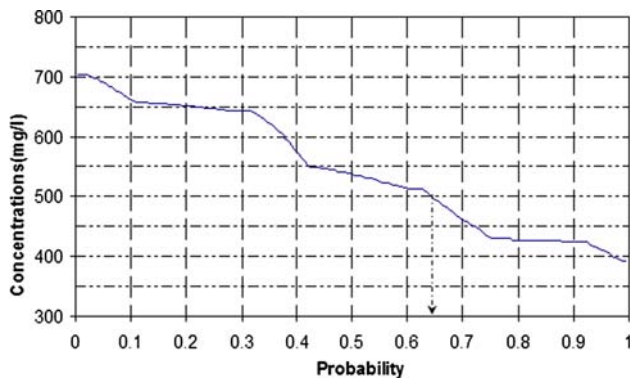
Fig. 13 Exceedance probabilities for observation well no. 21 under recharge and reduced pumping scenario

reduced pumping of about 0.67 can be accepted. Moreover, only about 5.6% of the investigated wells show a probability of exceeding the permissible limit of TH by more than 0.5 for recharge only and recharge with 25% reduced pumping, which is acceptable. The south western (West of Great canal) and cone of depression of the aquifer experiences the greatest environmental risk impact due overdraft remediation; hence a need for adequate monitoring and evaluation of groundwater quantity and quality prior to future remediation measures, and the understanding hydrogeological and geological factors affecting groundwater quantity and quality. The study concludes that remedial plan with recharge and pumping reduction scheduled such that, during summer, a reduction in pumping of not less than 15 % be done, while in winter not more than 25% reduction in pumping should be done, but the annual net effect should be that artificial recharge with reduced pumping at about 22% is achieved within the cone of depression, as it offers the most optimum risk-reduced remediation point where a trade off in terms of both quantity and quality combined for the Jining city centre in the cone of depression is achieved. However, it must be noted that all this must be done with close and continuous monitoring of the recovered groundwater quality and quantity. The use of water from proposed South-to-North water transfer for artificial recharge in combination with reduced pumping is a viable groundwater overdraft remedial venture. The method used in this study can also be used in other areas to assess the potential risks to aquifer due to groundwater overdraft remediation, and by so doing serious environmental impacts can be avoided.

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