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Research paper

Upgrading a regional groundwater level monitoring network for Beijing Plain, China

Yangxiao Zhou [a,*], Dianwei Dong [b], Jiurong Liu [b], Wenpeng Li [c]

[a] UNESCO-IHE Institute for Water Education, Westvest 7, 2611 AX Delft, Netherlands
[b] Beijing Institute of Geo-environmental Monitoring, No. 90, Beiwa Road, Beijing 100037, China
[c] China Institute for Geo-environmental Monitoring, No. 20, Dahuisi Road, Haidian District, Beijing 100081, China

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ABSTRACT

Monitoring of regional groundwater levels provides important information for quantifying groundwater depletion and assessing impacts on the environment. Historically, groundwater level monitoring wells in Beijing Plain, China, were installed for assessing groundwater resources and for monitoring the cone of depression. Monitoring wells are clustered around well fields and urban areas. There is urgent need to upgrade the existing monitoring wells to a regional groundwater level monitoring network to acquire information for integrated water resources management. A new method was proposed for designing a regional groundwater level monitoring network. The method is based on groundwater regime zone mapping. Groundwater regime zone map delineates distinct areas of possible different groundwater level variations and is useful for locating groundwater monitoring wells. This method was applied to Beijing Plain to upgrade a regional groundwater level monitoring network.

1. Introduction

Continuous decline of groundwater levels has been observed in many places of the world in the past half-century. It has indicated clearly the depletion of groundwater reserve in large scales (Konikow and Kendy, 2005). Groundwater depletion has been caused either by over-exploitation or reduction of groundwater recharge. The combination of these two causes has accelerated groundwater depletion in Beijing Plain, China. On one hand, groundwater abstraction continuously increases to meet demand for expanding industrial, agricultural and urban water supply. On the other hand, natural groundwater recharge has been affected due to the storage and diversion of inflowing rivers. Climate variability exerts extra pressure on the groundwater reserve. Significant decline of groundwater levels in the Beijing Plain has been observed since 1970's. Groundwater levels have decreased to historical low levels during the 8 consecutive dry years from 1999 to 2006. The total drop of groundwater levels amounts to more than 20 m since 1970's.

Quantification of the groundwater depletion provides very important information for effective groundwater resources management. Groundwater depletion can be assessed by integrating contour maps of groundwater level changes over the aquifer area or by using well calibrated groundwater models (McGuire et al., 2003). Both methods require long-term measurements of groundwater levels at regional scale. Regional groundwater depletion is rarely assessed because of the lack of these measurements. The regional monitoring network also provides important information required for water resources management (Van Bracht, 2001).

Historically, groundwater level monitoring in Beijing Plain started from monitoring water supply well fields and urban areas. Monitoring wells are clustered around well fields and the city. A regional groundwater level monitoring network does not exist. This paper reviewed the state of the art of regional groundwater level monitoring network design methods. A new method based on the delineation of groundwater regime zones was proposed. The method was applied to Beijing Plain to upgrade the existing monitoring wells into a regional groundwater level monitoring network.

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* Corresponding author. Tel.: +31 15 2151790; fax: +31 15 2122921.
E-mail address: y.zhou@unesco-ihe.org (Y. Zhou).

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2. Overview of groundwater level monitoring network design

2.1. Types of groundwater level monitoring networks

Groundwater monitoring generally starts in small scale with local problems. It evolves into regional or national monitoring networks focusing on both of local and regional problems. Regional scale groundwater level monitoring is necessary since most groundwater basins are regional; impacts of intensive human activities on groundwater have extended to the whole basin; and integrated water resources management requires regional groundwater level information at basin scale. Three stages of groundwater monitoring network development may be distinguished (Jousma and Roelofsen, 2004): (1) temporal monitoring networks for groundwater investigation or identification of local problems; (2) local groundwater monitoring networks for systematic monitoring of impacts of intensive groundwater withdrawal; and (3) national or regional groundwater monitoring networks for providing sufficient information for integrated water resources planning and management.

Objectives of groundwater level monitoring and intended use of groundwater level data determine types of monitoring networks. Objectives of groundwater level monitoring have been defined by Heath (1976), WMO (1994) and UNESCO (1998). In summary, data from a long-term regional groundwater level monitoring network may be used: (1) to characterize groundwater systems; (2) to analyze groundwater quantitative status; (3) to identify changes in groundwater recharge, storage and discharge; (4) to detect effects of climate change on groundwater resources; (5) to assess impacts of groundwater development; (6) to calibrate groundwater flow models; (7) to assess effectiveness of groundwater management and protection measures.

There are various classifications of groundwater level monitoring networks (Heath, 1976; WMO, 1989; UNESCO, 1998; Jousma and Roelofsen, 2004). Two main types of groundwater level monitoring networks are usually distinguished: basic (background or primary) monitoring networks and specific (or secondary) monitoring networks.

Basic monitoring networks are large scale regional or national monitoring networks designed for groundwater resources assessment and monitoring of regional groundwater regime and overall impacts. The basic network covers an independent groundwater basins or a complete country. Observation wells are installed in major aquifers at relatively large distances. Observations are taken with fixed low frequency for infinite long-term period.

Specific monitoring networks are local scale monitoring networks designed for monitoring of operations of groundwater systems for water supply or other specific purposes. The specific network focuses on local problems, for example, monitoring water table decline around pumping well fields, monitoring effects of irrigation schemes, and monitoring the groundwater levels in nature conservation areas. Network density should be sufficiently high to quantify effects and observation frequency should be sufficiently high to identify short-term variations.

Basic and specific monitoring networks are usually combined to form an integrated monitoring network. In this integrated monitoring network, basic monitoring wells provide reference conditions to assess local impacts observed by specific monitoring network. Regional low density basic wells serve the overall objectives while superimposed local high density wells focus on specific objectives. The classification of basic and specific networks may also be useful to divide the responsibility for monitoring between governmental organizations responsible for overall water management, and organizations with operation of specific water systems.

2.2. Design methods of groundwater level monitoring networks

In contrast to a growing large number of publications for designing groundwater quality monitoring networks (Loaiciga et al., 1991; ASCE, 2003), there are considerably less publications for designing groundwater level monitoring networks. From published references, methods for groundwater level monitoring network design can be classified into: (1) hydrogeological approach, (2) geostatistical approach, and (3) modeling approach.

Hydrogeological approach refers to principles and guidelines for groundwater level monitoring network design based on conceptual understanding of hydrogeological systems. Groundwater studies (UNESCO, 1972) provided an example of designing an observation well network to determine groundwater balance components in an experimental river basin. Peters (1972) proposed criteria for determining density of observation wells and record length for various intensities of hydrogeological investigations. Heath (1976) classified groundwater level observation wells into 3 networks: (1) hydrological network, (2) water management network, and (3) baseline network. Guidelines for required observation well density and observation frequency were proposed for these three networks. WMO (1989) issued a guideline for management of groundwater observation programmes. The groundwater observation networks were divided into a basic network, a specific network and a temporal network. Guidelines for choices of observation sites and frequency were provided for the design of a basic network. A guiding document was published by UNESCO (1998) on monitoring for groundwater management in (semi-)arid regions. Groundwater monitoring was classified into background monitoring and specific monitoring. The objective of a background groundwater quantity monitoring network was defined to provide time-varying information to characterize the initial stages of the development of a groundwater system. A new guideline on groundwater monitoring for general reference purposes was compiled by IGRAC (2006). A general reference groundwater monitoring programme is established for the reconnaissance of the groundwater system and the early stage of groundwater development and management. The objectives of the monitoring programme were defined to characterize regional groundwater systems, to detect trends in relation to groundwater use, to estimate potential for further groundwater development, and to provide historical reference data sets. Guideline and options for the design of groundwater monitoring networks for shallow and deep groundwater systems were provided.

Geostatistical techniques were not widely used for the design of groundwater level monitoring networks since it requires large number of measurements to estimate the spatial correlation structure, and a measure of network efficiency is difficult to define for multiple purposes of a groundwater level monitoring network (Taylor and Alley, 2001). Nevertheless, the variance of estimation errors for interpolating groundwater levels could be used as surrogate criteria for evaluating network efficiency. Kriging is a logical choice since it is not only the best interpolator, but also-provides the variance of interpolation error. Sophocleous et al. (1982) applied universal Kriging to analyze a groundwater level monitoring network for Northwest Kansas. Olea (1984) proposed to use the average standard error and the maximum standard error as two indices for measuring the global performance of sampling networks for spatial functions. A case study of the Equus Beds aquifer in the central Kansas was used to demonstrate the use of the method. Kriging method was also applied to redesign of groundwater level monitoring networks for the province of Gelderlands in The Netherlands (Van Bracht and Romijn, 1985).

In principle, numerical groundwater modeling could be used to identify key locations to measure groundwater levels to improve the model calibration. The integration of a numerical groundwater model with Kalman filtering offered possibility to design groundwater level observation networks (Zhou et al., 1991). However, the method was difficult to be applied to the design of regional groundwater level monitoring networks because of heavy computation requirement (Zhou and Van Geer, 1993).

3. Groundwater regime zone mapping method

Quantitative groundwater regime usually refers to groundwater balance state which is indicated by spatial distribution and temporal variations of groundwater levels. Groundwater levels are usually high in the recharge areas and low in the discharge areas, resulting in groundwater flow in general from recharge areas to discharge areas. The hydraulic gradient and flow pattern depend on heterogeneity and anisotropic characteristics of the aquifer systems. Temporal variation of groundwater levels is the response of the groundwater system to natural and artificial stresses in terms of groundwater recharge and discharge. The complexity and magnitude of the variation depend also on drainage resistance and storage properties of the aquifer systems. Therefore, the pattern of spatial and temporal variations of groundwater levels is the consequence of a combination of climatic, hydrological, geological, topographical, ecological and anthropogenic factors. These factors can be categorized to the following characteristics: (1) Land surface characteristics: depend on topography and land use which influence groundwater recharge and discharge processes; (2) Unsaturated zone characteristics: depend on soil/rock properties and depth to water table which act as a buffer zone to delay and damp groundwater responses to external stresses; (3) Saturated zone characteristics: consist of aquifer systems and properties and boundary conditions which largely determine spatial distribution pattern and temporal variations of groundwater levels; (4) Hydrological stresses: include precipitation, evapotranspiration and surface waters which are primary causes of natural variations of groundwater levels; and (5) Anthropogenic interferences: include surface water storage and diversion and groundwater development which are causes of trend of continuous groundwater level decrease.

Fig. 1 illustrates factors influencing groundwater regime. Groundwater regime is the response of the groundwater system to hydrological stresses and anthropogenic interferences. It is clear that a comprehensive analysis of all these factors will provide the basis to design a regional groundwater monitoring network to monitor groundwater regime.

Since all factors influencing groundwater regime vary in space, a combination of all these factors would result in distinct zones where there might exist different groundwater regime. These zones can be called groundwater regime zones. For example, groundwater level variations in the recharge zone are usually different from that in discharge zones. Therefore, systematic delineation of groundwater regime zones would be a logic approach for a comprehensive analysis of all groundwater regime factors.

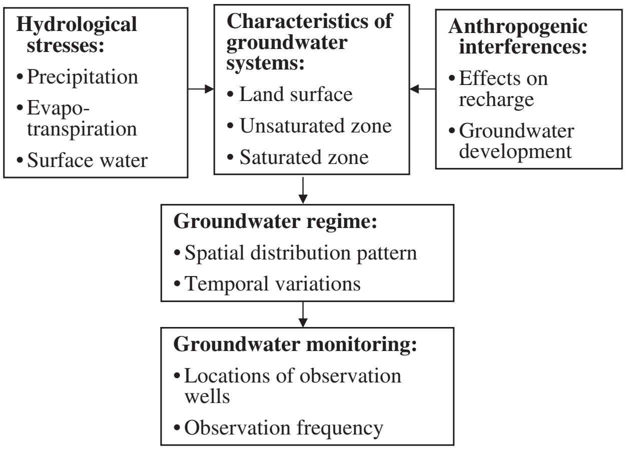

Figure 1. Factors influencing groundwater regime.

Fig. 2 proposes a flowchart to delineate groundwater regime zones. First, hydrogeological zones are delineated based on geomorphologic and geological maps. The hydrogeological zones represent specifically saturated zone characteristics. Second, combining water table depth and soil types above the water table will result in unsaturated zones. Third, groundwater recharge zones can be delineated using areal precipitation and land use types. Fourth, local influencing zones are identified around rivers, lakes, spring discharges, reservoirs, and well fields. Finally, the superposition of hydrogeological zones, unsaturated zones, recharge zones and influencing zones will result in distinct groundwater regime zones.

Hydrogeological mapping method is suited to implement the delineation of groundwater regime zones. Four thematic maps should be prepared: hydrogeological zone map, unsaturated zone map, recharge zone map and influencing zone map. These 4 thematic maps can then be superimposed to produce the groundwater regime zone map. In the last decades, wide availability of geographical information system (GIS) running on desktop computers has made GIS a popular automated tool for hydrogeological mapping. In a GIS environment, it is very efficient to create thematic maps. Map overlay functions can be used to combine thematic maps to produce a comprehensive map.

Groundwater regime zone map can be used to locate the observation wells. The underlining principle is that at least one observation well is required at each groundwater regime zone in order to capture different spatial and temporal variations of groundwater levels. By plotting locations of the existing observation wells on the groundwater regime zone map, one existing observation well should be selected for each regime zone. In those regime zones where there are no observation wells, one new observation well should be located at the center of each regime zone. Furthermore, in the selection of the existing observation wells and the design of new observation wells, the guidelines from WMO (1989) should be taken into account. Especially, pairs of observation wells should be located perpendicular to hydrogeological boundaries to monitor inflow and/or outflow conditions; pairs of observation wells should be located perpendicular to rivers and lakes to monitor the interaction between surface water and groundwater; separate piezometers should be installed at each aquifer to monitor groundwater levels in a multi-aquifer system; and observation wells should be located at sufficient distance from pumping wells to eliminate short-term dynamic effects.

The proposed groundwater regime zone mapping method falls in the category of hydrogeological approach for network design. Comparing to other hydrogeological approaches, the groundwater regime zone mapping method provides a systematic approach to delineate distinct groundwater regime zones using all physical factors and anthropogenic influences. At least one observation well for each regime zone leads to a preliminary design of a regional groundwater level monitoring network which could monitor adequately spatial and temporal variations of groundwater levels.

4. Design of a regional groundwater level monitoring network for Beijing Plain, China

4.1. *Natural settings of Beijing Plain*

Beijing Plain is located in the northwest corner of North China Plain (Fig. 3). Surrounded by mountains in west and north and bounded by the Hebei Province and Tianjin City in east and south,

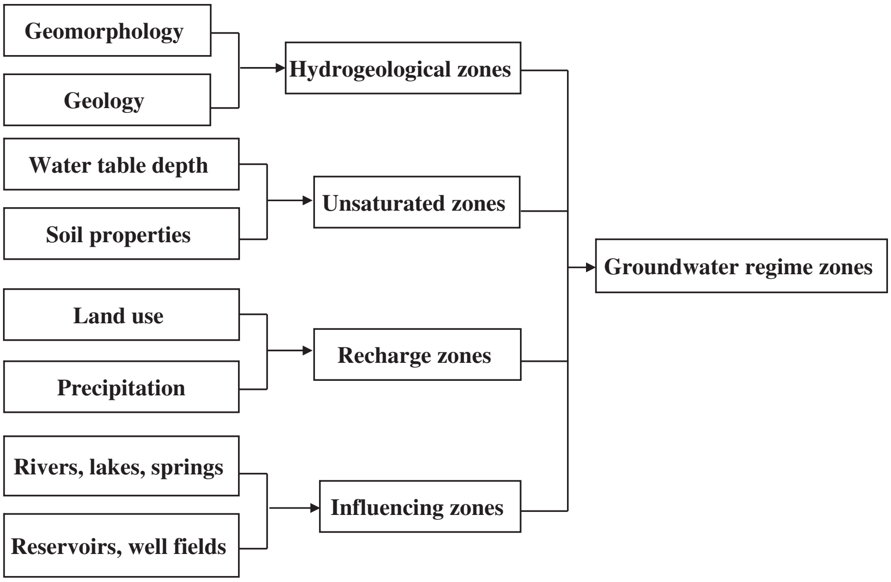

Figure 2. Delineation of groundwater regime zones.

the area of the Beijing Plain is around 6032 km^2. The Beijing Plain is formed by alluvial fans and plains of two largest rivers and several small rivers. Land elevation is high in northwest and gradually decreases toward southeast. The capital city of China, Beijing, is located in the middle west of the Beijing Plain (Fig. 4).

Beijing Plain consists of Quaternary deposits formed by alluvial fans and plains. The thickness of Quaternary varies from tens meters to more than 500 m. The aquifer system is complex with variable sediment thickness and lithology. From the alluvial fans to plain, the sediment thickness increases and grain size decreases, aquifer systems change from a single gravel aquifer to multiple aquifer systems of sand layers separated by silt and clay layers. The water bearing layers within a depth of around 50 m is called the shallow aquifer while the aquifer with the depth of more than 50 m is called the deep aquifer. The large part of the shallow aquifer is unconfined. It receives all natural groundwater recharge. Majority of agricultural wells are located in the shallow aquifer. Some water supply well fields are installed in the shallow aquifer on the top of alluvial fans. The deep aquifers are confined. The recharge to the deep aquifers comes mainly from the leakage of the shallow aquifer. Majority of industrial water supply wells and some drinking water well fields are drilled in the deep aquifer.

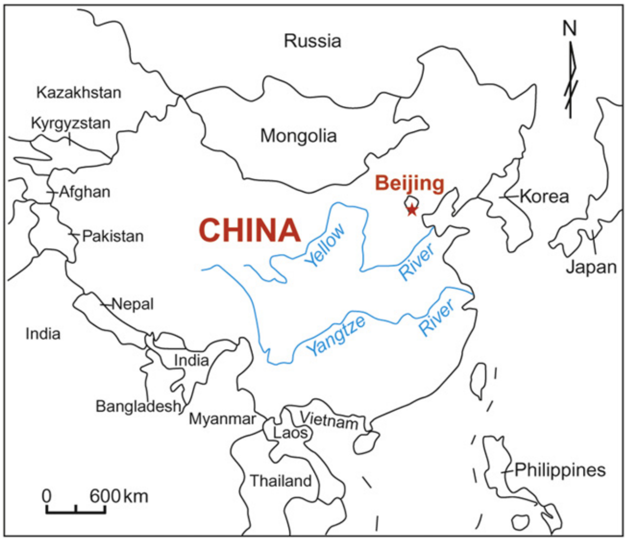

Figure 3. Location map of the study area.

The contour map of the shallow groundwater levels in the Beijing Plain (Fig. 5) shows in general groundwater flows from north and west of recharge boundaries to southwest direction. However, intensive groundwater withdraws for urban and industrial water supplies have alternated the regional flow pattern. Three areas of groundwater level depression can be seen very clearly. A large cone of depression is formed in the east middle area. The area is located in the east suburb of the Beijing City. The aquifer consists of multiple sand layers separated by silty clay layers. The recharge is comparatively small. The direct recharge from precipitation infiltration and lateral inflow is main recharge. Groundwater abstraction for industrial and township water supply has caused the cone of the depression. Another cone of depression is found in the recharge area of Chaobai River in the north. Although the aquifer in the area consists of thick layers of gravel and sand, groundwater recharge is largely reduced since the river becomes dry. The continuous abstraction of a permanent well field and the new withdrawal from an emergence well field to combat drought since 2003 have caused this cone of depression. The third large area of groundwater depression occurred in the southwest suburb of Beijing City. Several water supply well fields were developed for Beijing City. Groundwater abstraction from these well fields combined with the decrease of groundwater recharge from the Yongding River is primary factors of causing this depression area.

4.2. Groundwater level monitoring in Beijing Plain

Groundwater level monitoring in Beijing Plain started from 1956 around pumping well fields in the vicinity of Beijing City. By 1963 there were 825 wells where groundwater levels were observed regularly, but most of wells were production wells in rural areas and were observed by local residents. Groundwater monitoring activity was heavily disturbed during the 10 years of Cultural Revolution from 1966 to 1976. Monitoring of production wells was virtually stopped. By 1983 most observation wells were recovered and observations of production wells were resumed. The total

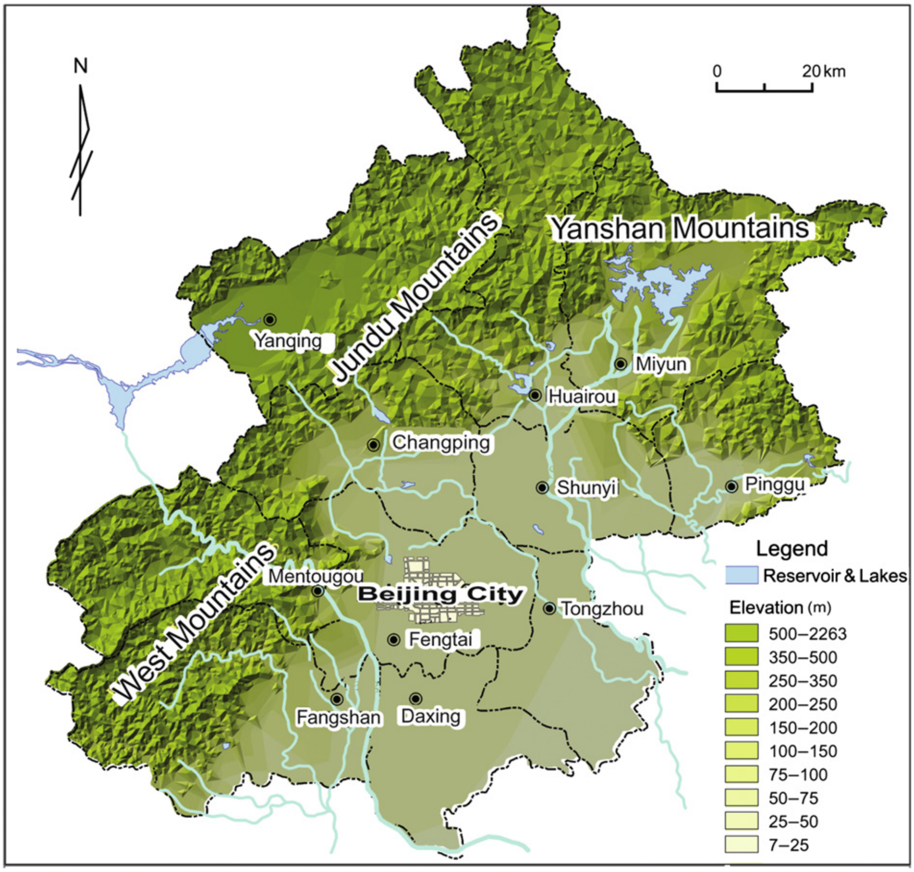

Figure 4. Topographic map of Beijing Plain.

observation wells were around 750. The rapid expansion of Beijing City from 1990's has destroyed many groundwater monitoring wells in urban areas. At present there are about 650 observation wells, of which 150 are professional observation wells and 500 are production wells. The professional observation wells were drilled specifically for groundwater monitoring, well screens were installed only in a specific aquifer, and observations were taken by technical staff 6 times a month. Production wells are used for domestic water supply or irrigation, many of production wells penetrate several aquifers, and observations are taken by hired local residents.

Monitoring well inventory was carried out to assess status of present groundwater level monitoring wells in 2004. It was found that 43 out of 150 professional monitoring wells were clogged and were cleaned up in 2005. In principle production wells should not be used to monitor the regional groundwater levels. However, due to budget limitations, 150 wells out of 500 production wells have the good records and can be continued to measure groundwater levels. There are in total 153 observation wells for monitoring groundwater levels in the shallow unconfined aquifer, in which 63 wells are professional observation wells and 90 are production wells. The remaining 147 wells are distributed in deep confined aquifers.

Groundwater has provided more than 70% of water supply for Beijing City since 1980's. Long-term over-exploitation of groundwater in Beijing Plain has resulted in the formation of large cones of groundwater depression. Groundwater level at the center of the depression in the east suburb of the Beijing City has dropped more than 25 m since 1990. Decrease of groundwater heads in the confined aquifers has induced land subsidence. The area of land subsidence coincides with the area of depression. The accumulated land subsidence has reached 850 mm in the center. It has caused cracks in buildings, break of some pipelines and instability of foundations (Beijing Hydrogeological Unit, 2004).

Fig. 6 shows groundwater levels from a professional observation well in the Yongding River alluvial fan. In general groundwater levels have dropped 26 m from 1958 to 2006. Several stages of historical changes of groundwater levels can be observed. There was a slow decrease of groundwater level from 1958 to 1974. Groundwater levels had dropped only 3 m in 17 years. The annual variation of groundwater level was also small. Followed is a faster decrease of groundwater level from 1975 to 1985 in a drought period. Groundwater level dropped 16 m in 10 years. Groundwater level was stabilized from 1986 to 1994. The wet year 1994–1996 caused an increase of groundwater levels from 1996 to 1997. Groundwater level decreased again from 1999 to 2006 following the last drought period. It had dropped 14 m in 8 years. Every drought period was associated with a large scale groundwater development to meet demand of water for irrigation and urban water supply. This accelerated groundwater level decrease during the drought years.

The present groundwater level monitoring wells couldn't adequately monitor regional trend of groundwater level variations in Beijing Plain. The number of multiple piezometers is limited and could not determine the vertical flow pattern. The number of observation wells is not sufficient to monitor the extension of the depression cone with required accuracy. Furthermore, there are few professional monitoring wells on the tops of alluvial fans to monitor groundwater level changes in recharge areas. There are also limited number of observation wells to monitor the water exchange between rivers and aquifers. It is necessary to upgrade present groundwater level monitoring wells into a regional groundwater

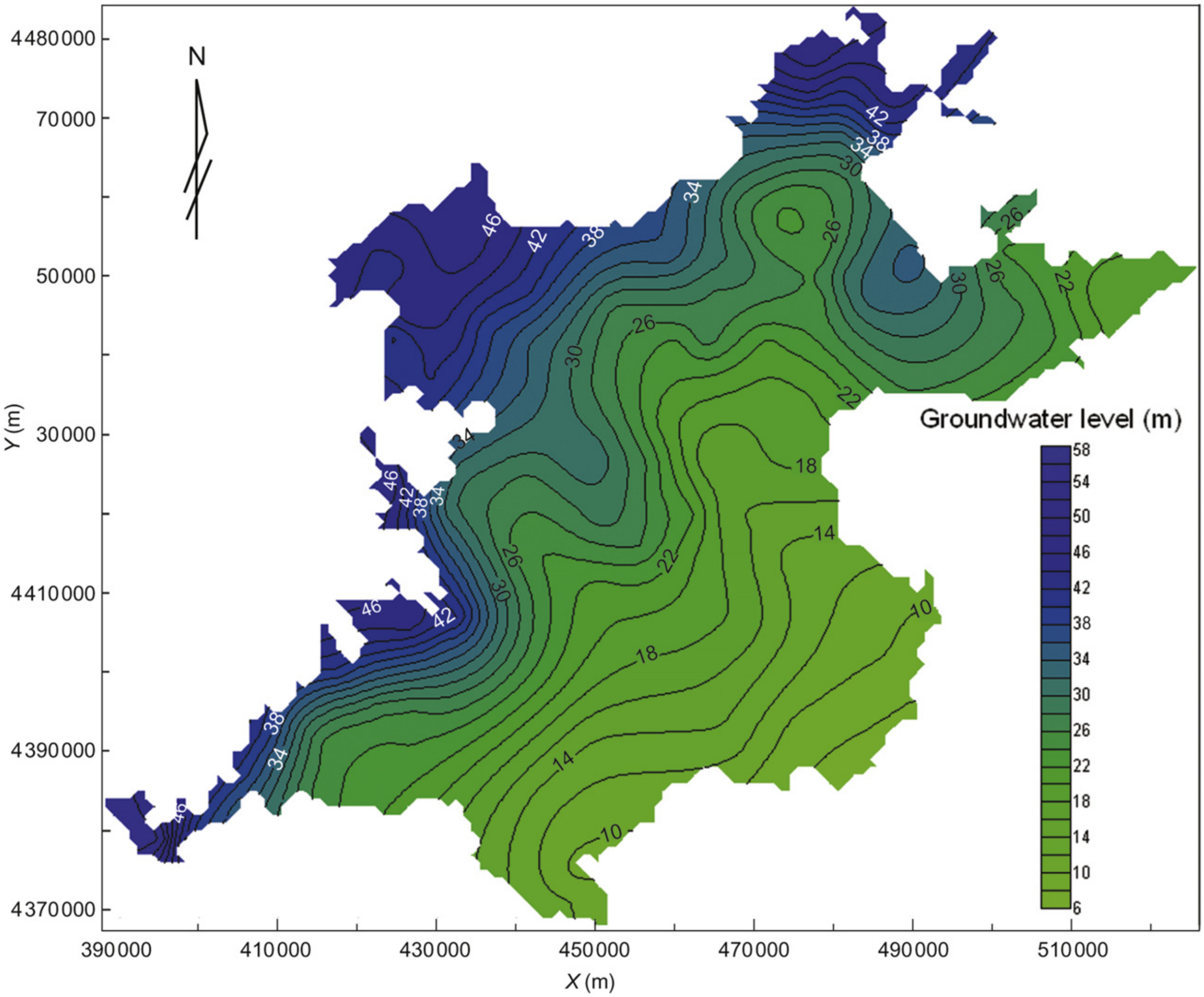

Figure 5. Contour map of groundwater levels in the shallow aquifer of Beijing Plain in June 2005.

level monitoring network. The objectives of the regional groundwater level monitoring network in Beijing Plain are to assess the quantitative status of groundwater systems and to detect the trend of groundwater level changes. The network will provide important information for groundwater resources management in Beijing Plain.

4.3. Design of a regional groundwater level monitoring network for Beijing Plain

A groundwater regime zone map was prepared in order to delineate possible different regime zones in Beijing Plain. This map was the result of the superimposition of 4 thematic maps:

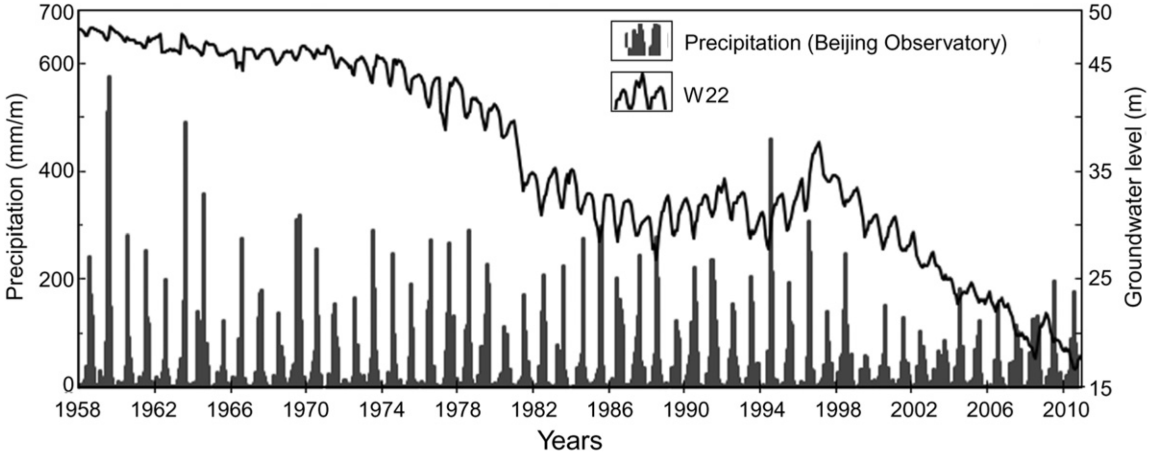

Figure 6. Changes of groundwater levels in Beijing Plain.

hydrogeological zone map, unsaturated zone map, groundwater recharge zone map and local influencing zone map.

The hydrogeological zone map was created using the geomorphologic and geological maps. From the geomorphology, the area is divided into 5 hydrogeological sub-systems: (I) Juma river alluvial fan; (II) Yongding river alluvial fan-plain; (III) Nankou-Wenyu alluvial fan-plain; (IV) Chaobai river alluvial fan-plain; and (V) Jiyun river alluvial fan. From the geology, the aquifer lithology is classified into 5 media: (1) single layer of pebbles and gravels; (2) multiple layers of pebbles and gravels; (3) multiple gravel layers interbedded with a few sand layers; (4) multiple sand layers interbedded with a few gravel layers; and (5) multiple sand layers. Superposition of 5 hydrogeological sub-systems and 5 aquifer lithology classes results in a total of 30 hydrogeological zones (Fig. 7). Each hydrogeological zone is coded with the name consisting of the location of groundwater sub-system and aquifer lithology. For example, one hydrogeological zone is the Yongding River sub-system-single layer of pebbles and gravels. Another is the Yongding River sub-system-multiple sand layers interbedded with a few gravel layers. Clearly these two hydrogeological zones will have different groundwater dynamics.

Unsaturated zone map was delineated using the water table depth map and borehole columns. Soil properties from land surface to water table were analyzed from nearly 800 borehole data. The soil types in the unsaturated zone were classified into 8 groups and their distribution is shown in Fig. 8. Gravels and sand are mainly distributed in alluvial fans. Clay dominated soils are distributed mainly in areas between alluvial fans.

Groundwater recharge in Beijing Plain is mainly from the infiltration of precipitation and depends on precipitation, land use and unsaturated zone characteristics. A precipitation infiltration coefficient zone map was created according to lithology in unsaturated zone and water table depth (Beijing Hydrogeological Unit, 1998). Thiessen polygons of areal precipitation were prepared from long-term (1959–2006) annual average precipitation of 11 stations in Beijing Plain. The multiplication of the infiltration coefficient zone map and areal precipitation estimated the average annual groundwater recharge. The annual groundwater recharge was

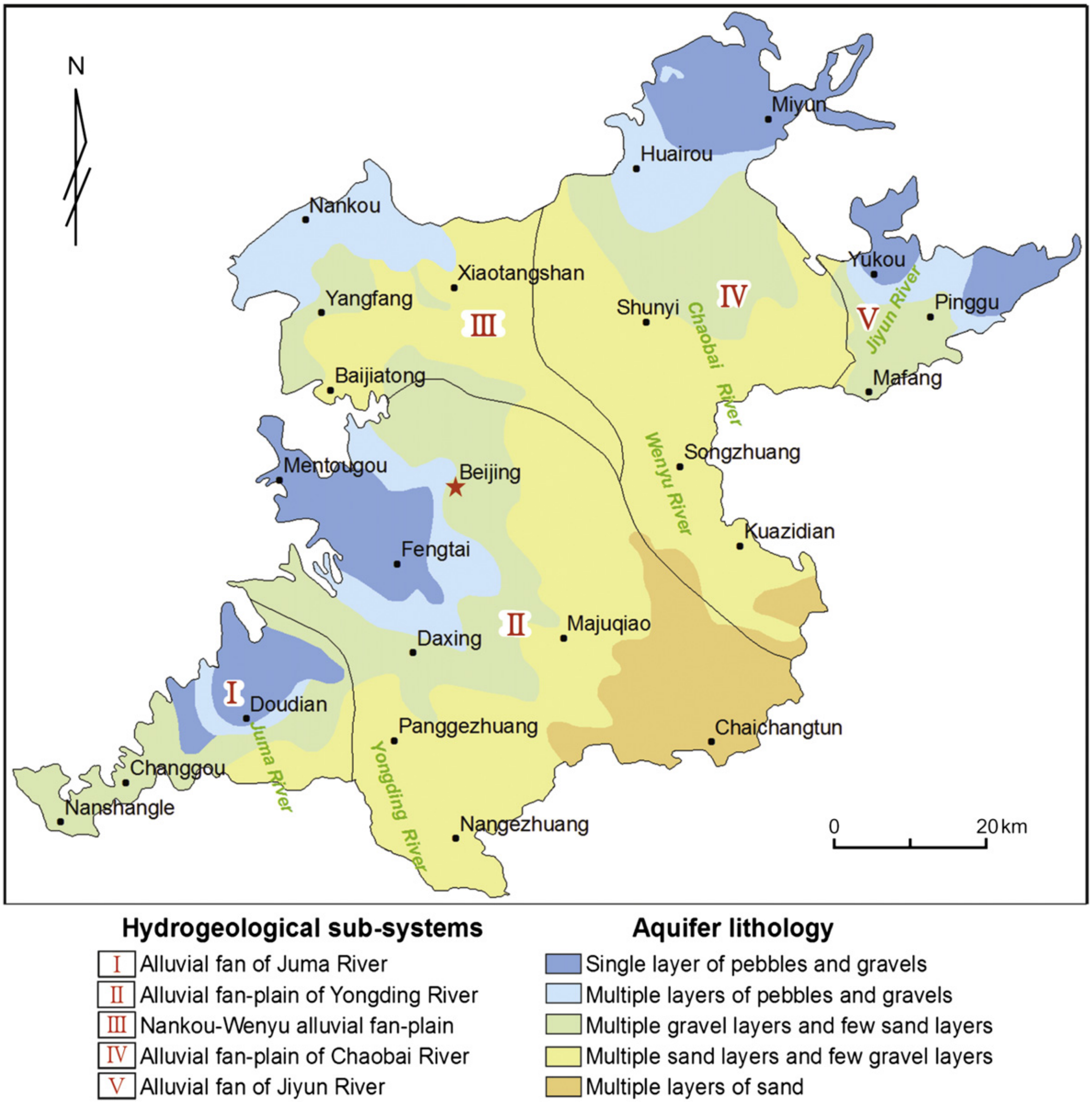

Figure 7. Hydrogeological zone map.

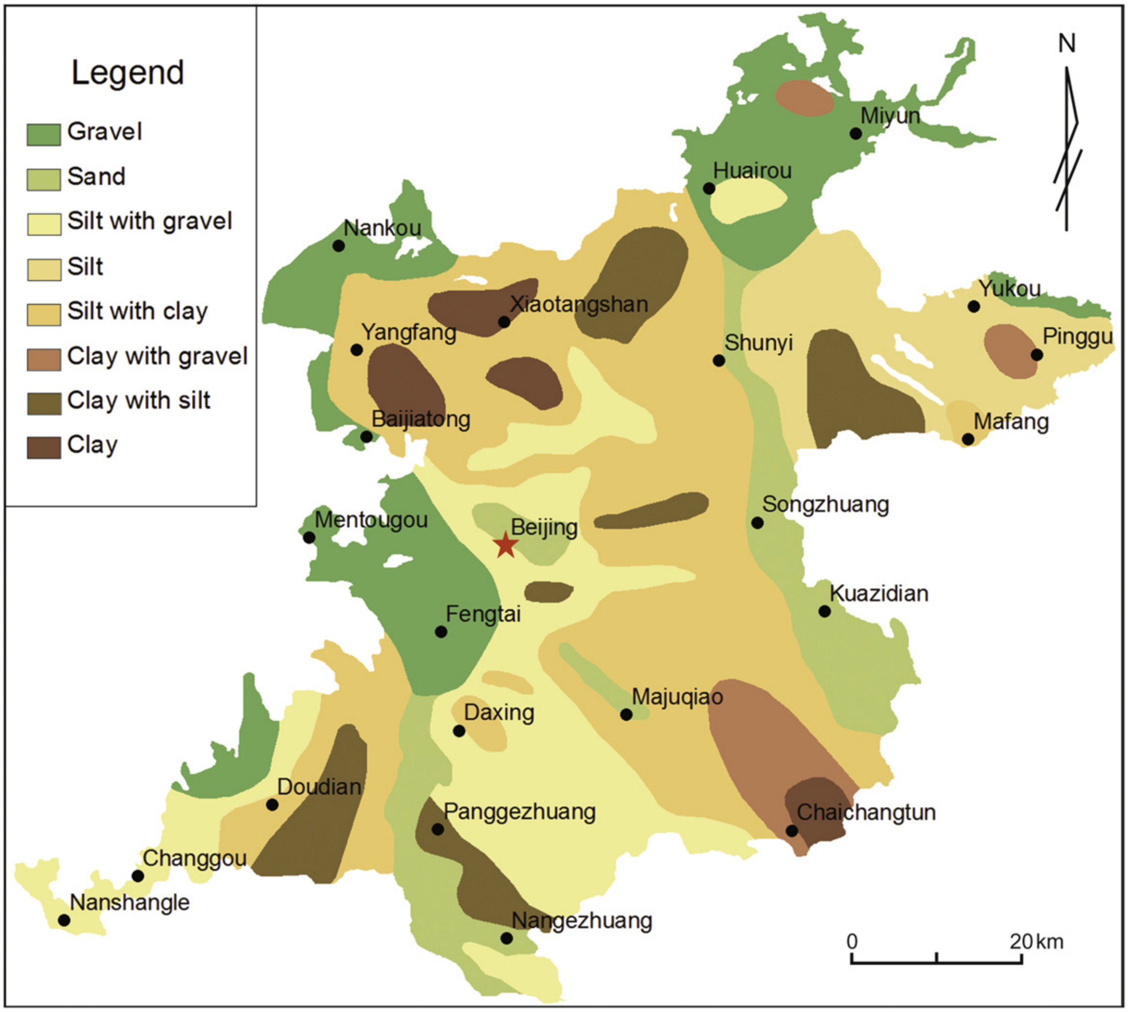

Figure 8. Unsaturated zone map.

classified into 4 categories with a class width of 60 mm/yr as shown in Fig. 9. The area distribution of recharge zones corresponds very well to the hydrogeology of the area. Strong recharge areas are located in the inclined piedmont and top alluvial fans. Good recharge areas are located in riverbeds. The moderate recharge areas are found in the alluvial plain. The weak recharge area is in the urban area.

The influencing zone map (Fig. 10) includes the cones of depressions, large water supply well fields and rivers. The cones of depressions were roughly determined by subtracting groundwater level contour map of 1965 with the contour map of 2005. The present riverbeds were used to indicate the influence of rivers. Locations of large water supply well fields were used to indicate influence of local intensive abstraction.

By superposing the above 4 thematic maps, a groundwater regime zone map was created for Beijing Plain (Fig. 11). A total of 260 groundwater regime zones were identified. These regime zones are unique combinations of hydrogeological zones, unsaturated zones, recharge zones, and influencing zones. Each regime zone is coded with the names of hydrogeological zone, unsaturated zone, recharge zone and influencing zone. The regime zones may represent different spatial and temporal variations of groundwater levels in Beijing Plain. For example, one regime zone is located on the top of alluvial fan of the Yongding River. The coding name is the Yongding River sub-system (hydrogeological sub-system)-single layer of pebbles and gravels (aquifer lithology)-gravel (unsaturated zone)-strong recharge (recharge zone)-Yongding River (local influencing zone). Because of high permeability in the unsaturated and saturated zone and good recharge from rainfall and river leakage, the characteristics of groundwater in this zone are: large seasonal variations, dominant horizontal flow and short residence time. Another zone is located in the alluvial plain of the Yongding River. The coding name of this zone is the Yongding River sub-system-multiple sand layers and a few gravel layers-silt-moderate recharge. The characteristics of groundwater in this zone could be: small seasonal variations, vertical flow between aquifers, slow horizontal flow and longer residence time.

The groundwater regime zone map was used to design a regional groundwater level monitoring network for Beijing Plain. The locations of 153 shallow monitoring wells (blue circle) were plotted on the groundwater regime zone map (Fig. 11). Groundwater regime zones where there are no existing monitoring wells indicate a need to add a new observation well. Priorities were given to mountain front recharge zones, river belts and depression cones. A total of 108 new wells were designed (Fig. 11): 36 wells (light blue triangle) were designed to monitor mountain front recharges; 38 wells (light blue circle) to monitor interactions with rivers; and 34 wells (light blue diamond) to monitor groundwater levels in regime zones of no observation wells. In total 261 observation wells form a preliminary regional groundwater level monitoring network for

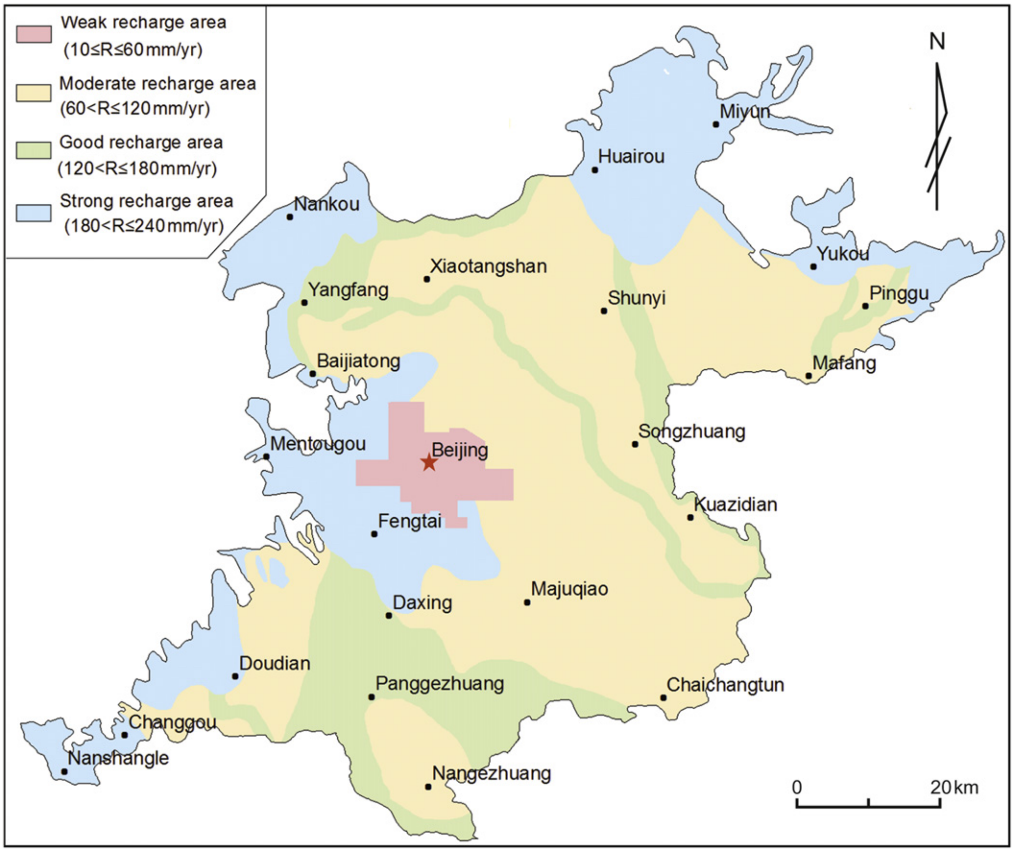

Figure 9. Groundwater recharge zone map.

Beijing Plain. These observation wells were plotted also on the 4 thematic maps to check the coverage of aquifer lithology, recharge and influence zones.

In principle, in locations where several aquifers exist, multiple piezometers should be installed in observation wells to monitor groundwater levels in different aquifers. These data are very important to determine vertical groundwater flow through aquifers and to construct three dimensional groundwater flow patterns in Beijing Plain. At present, there are not many observation wells at each confined aquifer. The newly designed observation wells should be installed with multiple piezometers in multiple aquifers.

The regime zone mapping method may result in a number of alternative monitoring networks when different number of classes is defined in 4 thematic maps. In Beijing Plain case, the delineation of the hydrogeological zones and unsaturated zones is based on geomorphology, geology and soil properties. The number and boundaries of these zones should not vary very much. The local influencing zones should not change also since they are based on actual locations of riverbeds, well fields, and cones of depression. Groundwater recharge zones may vary depending on the number of classes chosen. A larger number of classes will result in a larger number of regime zones. Since the objective of the regional groundwater monitoring network aims to characterize regional groundwater regime, a small number of classes of the recharge was chosen. Therefore, a relatively small number of regime zones were delineated. When one monitoring well per regime zone is selected, a preliminary regional groundwater monitoring network with relatively small number of monitoring wells was designed. This preliminary network can be improved in future when the measured data are systematically analyzed to characterize the spatial and temporal regimes.

Ideally, the cost-benefit of the proposed network should be assessed. Although the cost of the monitoring network can be estimated, it is difficult to quantify the benefit. In practice, surrogate criteria are often used, such as the standard deviation of the interpolation error (Sophocleous, 1982; Van Bracht and Romijn, 1985; Zhou et al., 1991). The spatial distribution of groundwater levels is characterized by groundwater level contour maps. Kriging is often used to interpolate groundwater level measurements to create contour maps of groundwater levels. The accuracy of interpolation is usually used as an indicator of the network effectiveness. The accuracy is expressed as the Kriging standard deviation of interpolation errors, which depends on spatial correlation structure of groundwater levels and number and locations of monitoring wells. The spatial correlation structure of groundwater levels in Beijing Plain was estimated from measurements of groundwater levels in 2005 in the form of a variogram model. The cross-validation found a linear variogram model with a nugget effect of 13 m^2 and a slope of 0.0025 m^2/m. This linear variogram model was used to construct the groundwater level contour map (Fig. 5) and to calculate the standard deviation of interpolation errors of the present monitoring network and to simulate the standard deviation of interpolation errors of the newly designed network. The differences of the Kriging standard deviation between the newly designed and present monitoring network show the reduction of the interpolation errors (Fig. 12) with newly designed monitoring wells. The reduction of interpolation errors varies from 0.5 to 4.5 m. In areas where the new monitoring wells are added, the reduction of the interpolation errors is significant.

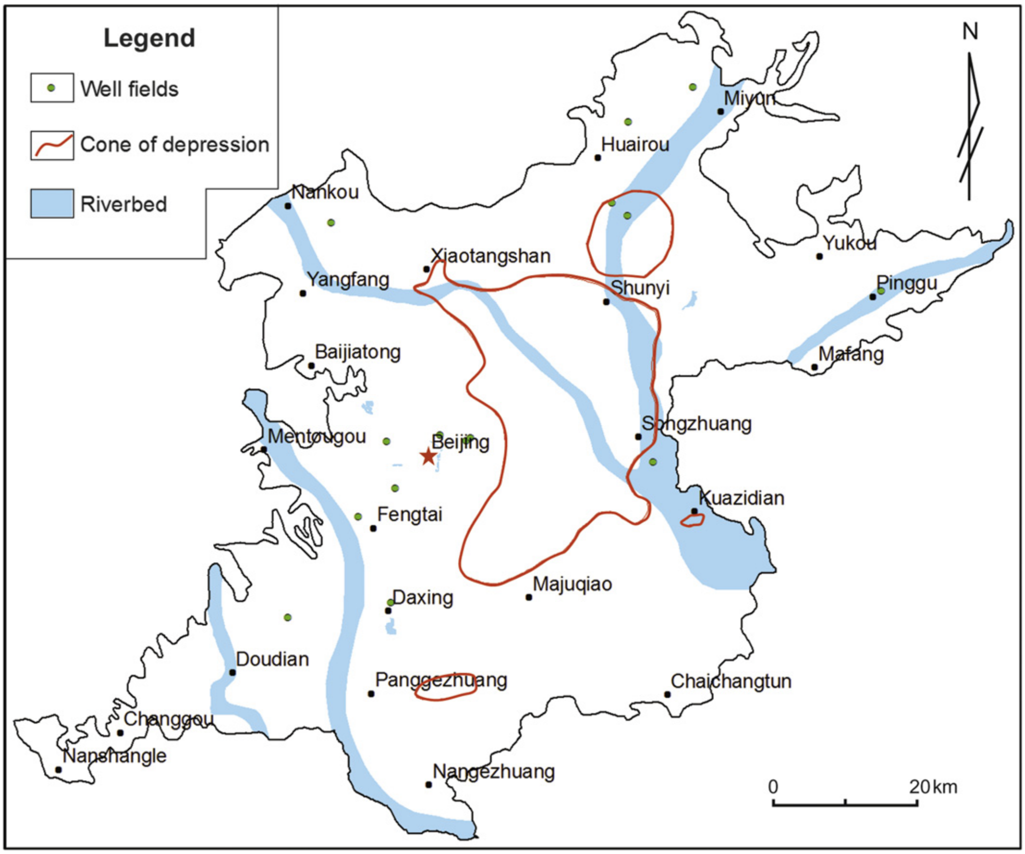

Figure 10. Local influencing zone map.

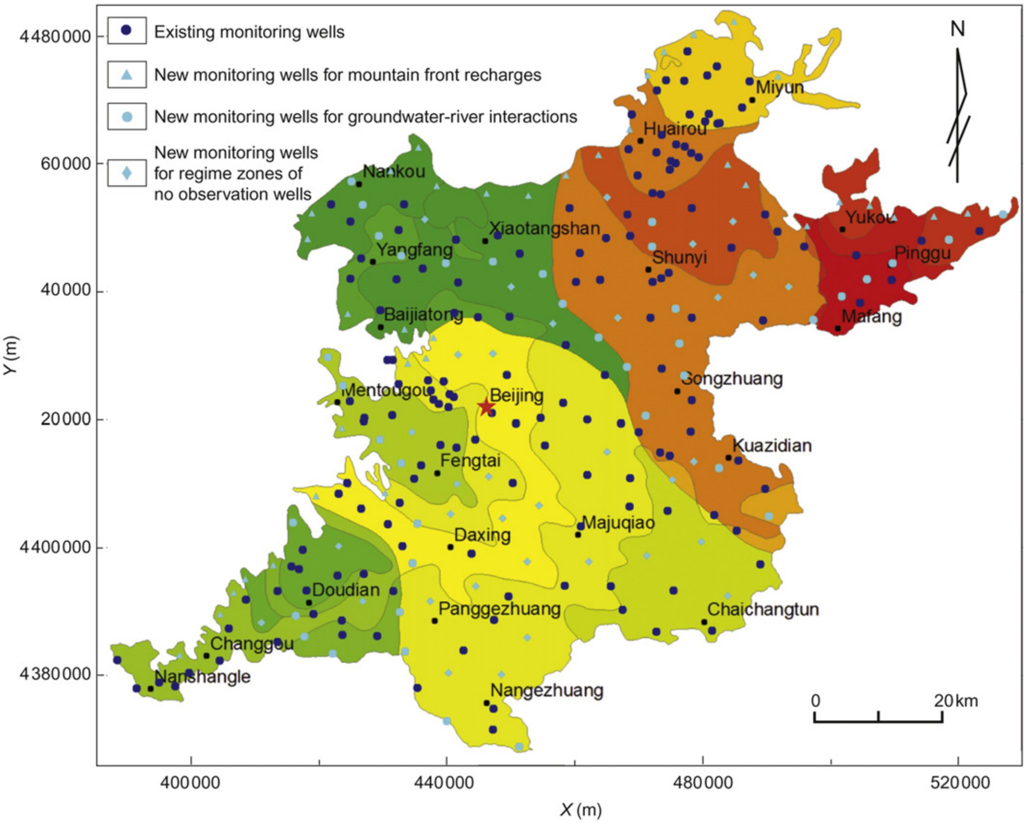

Figure 11. Groundwater regime zone map and locations of observation wells in Beijing Plain.

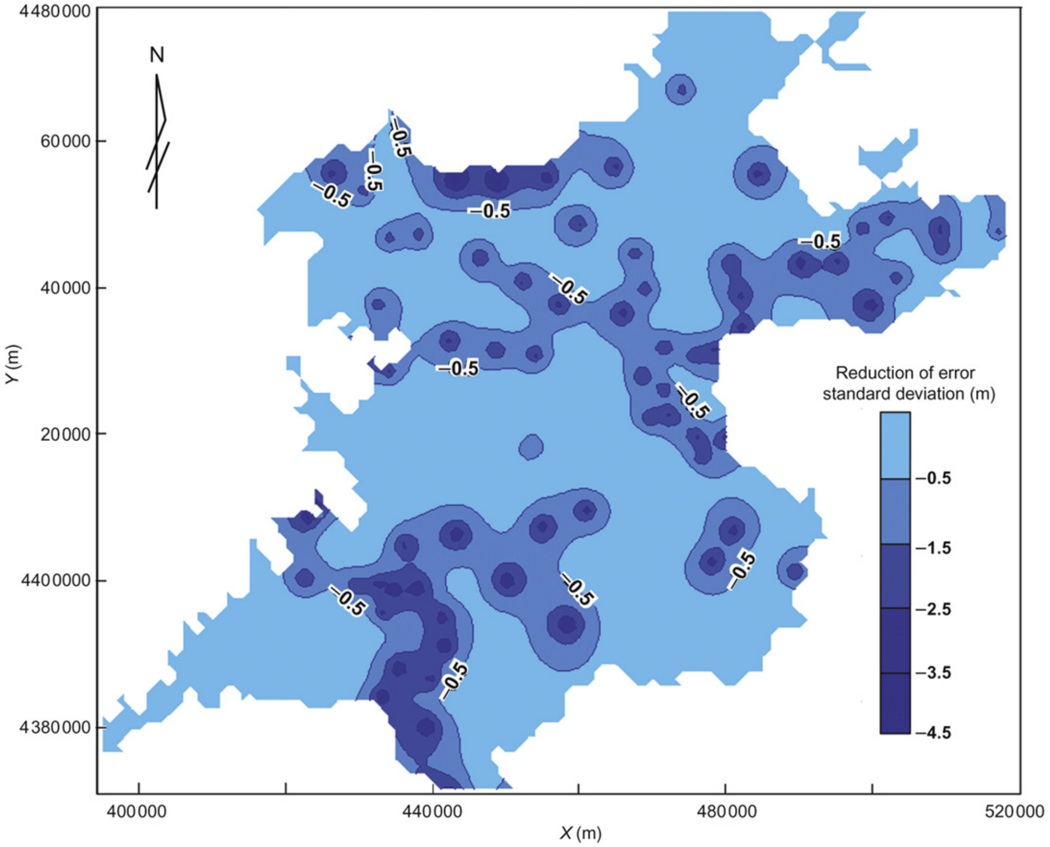

Figure 12. Contour map of reduction of Kriging interpolation error standard deviation (in meters) with the newly designed regional groundwater level monitoring network.

5. Conclusions

Regional groundwater level monitoring provides important information for groundwater resources management and basic data for all groundwater studies. Adequate information can be obtained from a well-designed monitoring network. Groundwater regime zone mapping can identify distinct areas where groundwater level may have unique spatiotemporal characteristics. Therefore, groundwater regime zone map could be used to locate groundwater level observation wells.

Groundwater has provided more than 70% of water supply in Beijing Plain. Over-exploitation of groundwater since 1970's has caused continuous decline of groundwater levels. An exceptionally long-spell of drought in last 8 years has accelerated rapid decrease of groundwater levels. Regular monitoring of groundwater levels in Beijing Plain since 1950's has been very useful in detecting trend of groundwater level decrease. However, groundwater level monitoring in Beijing Plain is still problem-oriented and monitoring wells are concentrated mainly in well fields and urban areas. It is time to upgrade the network to a regional groundwater level monitoring network focusing also on hydrogeological process monitoring. A regional groundwater level monitoring network has been designed using groundwater regime zone map as a reference. Since observation wells in the deep confined aquifers are limited, newly designed observation wells should be installed with multiple piezometers to monitor groundwater levels in different aquifers. These data are important to determine the vertical groundwater flow through aquifers and analysis of three dimensional groundwater flow patterns in Beijing Plain.

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