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A three-dimensional model and its potential application to spring protection

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Abstract Withdrawal of groundwater can dry up springs. It is, however, often difficult to determine the exact causes for the depletion of spring flow by the traditional methods. A 3-D geological model is presented in this paper to explore the groundwater flow conditions in the aquifers that feed springs. Because of the various geological data in spring areas, a date integration technique is adopted to ensure the accuracy of the model. This model is implemented in the spring protection program in Jinan City, China, and the reasons for the drying up of the springs in the city are studied. The proposed model would be particularly helpful in the spring protection, and the appropriate application of the model would result in economic and social benefits of the city.

Keywords Geological modeling · Water resource simulation · Spring protection · Jinan · China

Introduction

Jinan City, China, is known for its springs. Since 1980s, the groundwater levels in the aquifer that feeds the springs have declined significantly because of overplowing and overexploitation. Most of the springs have become intermittent in their discharges; some of them have ceased flow. Many studies have been performed to protect the springs. A successive large-scale link experiments on the spring sources were made to determine the characteristics of the groundwater flow in the karst area (Zhang and others 1998). The study on controlling parameters of the Jinan springs indicated the maximum available amount of groundwater (Li and others 2002). The development of geographic information system (GIS)-based models showed that the landscape spatial pattern had changed since 1995 (Chen and Sun 2004). Several studies indicated that the integrated water resource analysis and management in a given jurisdiction were capable of identifying the feasible water allocations (Meng 2003; Wu 2003; Shang and Wang 2000). The support of provisional government and local regulatory agencies has led to a series of measures, including diversion of water from the Yellow River to Jinan, artificial recharge of groundwater, rational exploitation of groundwater, and better utilization of surface water. However, these spring protection efforts have not resulted in anticipated effects because several key problems, including the geologic conditions of the Jinan spring area, have not been solved.

With the advancement of the 3D modeling and the visualization techniques, geological data can be used to construct 3D models in complex geological environments (Duvinage and Mallet 2000; Wendland et al. 2003; Kim et al. 2004; Wu et al. 2005). In this paper, the 3D modeling technique involving, data integration, 3D

geological modeling, and water resource simulation, is used to explore the causes of the spring depletion at Jinan City.

The main challenge raised by the 3D modeling is the variety of the available data, both in nature and reliability (Winkler et al. 1999). A data integration technique, which consists of source-oriented integration and object-oriented integration, is designed to utilize the various geological data in the paper and to keep the data consistent in the model.

The existing 3D geological modeling systems rely heavily on data from boreholes and geologic cross sections (Zehnder and Allmendinger 2000 ; Duvinage and Mallet 2000; Sirakov and Muge 2001; Lemon and Jones 2003). However, like other study sites, the available geological data is sparse and undersampled in the Jinan spring area. It is difficult to effectively establish the geological models with the traditional methods. Therefore, an application-oriented method is proposed to integrate the multisource data for the 3D geological modeling. The 3D model was constructed based on the existing 2D GIS database and using geological boundaries, Digital elevation model (DEM) data, boreholes, cross sections, fault surfaces, and remote sensing images.

Estimating groundwater recharge is another challenge for hydrologists because direct measurements are costly and difficult to implement (Zacharias and others 2003). In this paper, a unique methodology is designed in the 3D model to implement the water resource simulation, including gullies, lakes, and groundwater level. This methodology can provide a reliable, cost-effective platform for surface water and groundwater simulation. It will also provide additional information and references to the government for policy making and conservation of the spring water.

Data integration

Source-oriented integration

Jinan, the capital city of Shandong Province on China's east coast, is a regional, political, economic, cultural, scientific, and educational center. Jinan is near Mountains Tai to the south and neighbors the Yellow River on the north. The terrain of the territory of Jinan slopes down from the south to the north and its landforms vary from hills and inclined plains in front of the mountains to the alluvial plains of the Yellow River. The city has a continental climate with an annual average rainfall of 647 mm. It covers an area of 8,177 km^2. The Jinan spring area is located between fault F_1 and fault F_2, with an area of 1,486 km^2. It is a karst water system. The study region is inside the polygon, as shown in Fig. 1. The stratigraphic sequence consists of powdery clay, conglomerate and clay of the Quaternary age, grit of the Permian age, diorite of the Carboniferous age, limestone of the Ordovician age, as well as the Fengshan, Gushan, and Zhangxia Formations of the Cambrian age. The zone forms a monocline structure dipping slightly toward north. Generally, concealed faults are the primary geologic structure. The major stratum exposed in the study area is the Ordovician limestone. The Ordovician limestone is also the most important aquifer, which is underlain by the entire city, with groundwater levels 10~100 m below the surface.

Data of the regional hydrogeology, engineering geology, and environmental geology have been accumulated through various studies over the years. In order to utilize these available data for the 3D simulation, the source-oriented integration is proposed. The source-oriented integration offers a visual, physical, and uniform channel in the 3D space. It aims to support the interoperability of various data sources and make any possible form of geological data to be stored, processed, displayed, and manipulated in the same coordination system.

The geological data are classified into three types: direct data, indirect data, and assistant data. Direct data, such as borehole data, property data, and springs, is original sampling data obtained by direct observations and survey, and is highly accurate. It is utilized directly in the 3D modeling system and is managed and stored with databases in the MS Access, Oracle, and other formats. Indirect data, is also original but has different precisions with different resolutions of graphs, such as boundaries, faults, DEM derived from geological maps, topographic maps and structural geology maps, 2D/3D seismic reflection data, exploring data, as well as contours of water table, gullies, lakes, and so on. This type of data should be stored as files after being digitized. However, this kind of data cannot be used as direct inputs for the 3D modeling system. To integrate the indirect data, they need to be digitized using the existing software systems like AutoCAD, ArcView GIS or other interpretative software, and these digitized data need to be converted into the 3D modeling system by employing the CAD/GIS Data Conversion Interface (DCI) as well as DEM DCI. Assistant data will be used in the process of 3D modeling as icons like 2D/3D primitives, and texture maps including remote sensing image and scanned maps.

Object-oriented integration

Once the diverse kinds of geological data are integrated into the 3D modeling system, geometrical objects abstracted from these data are analyzed and mapped into different abstract levels of space. Point objects are at the bottom level and then line and polygon objects. The data structures are shown in Table 1. A point

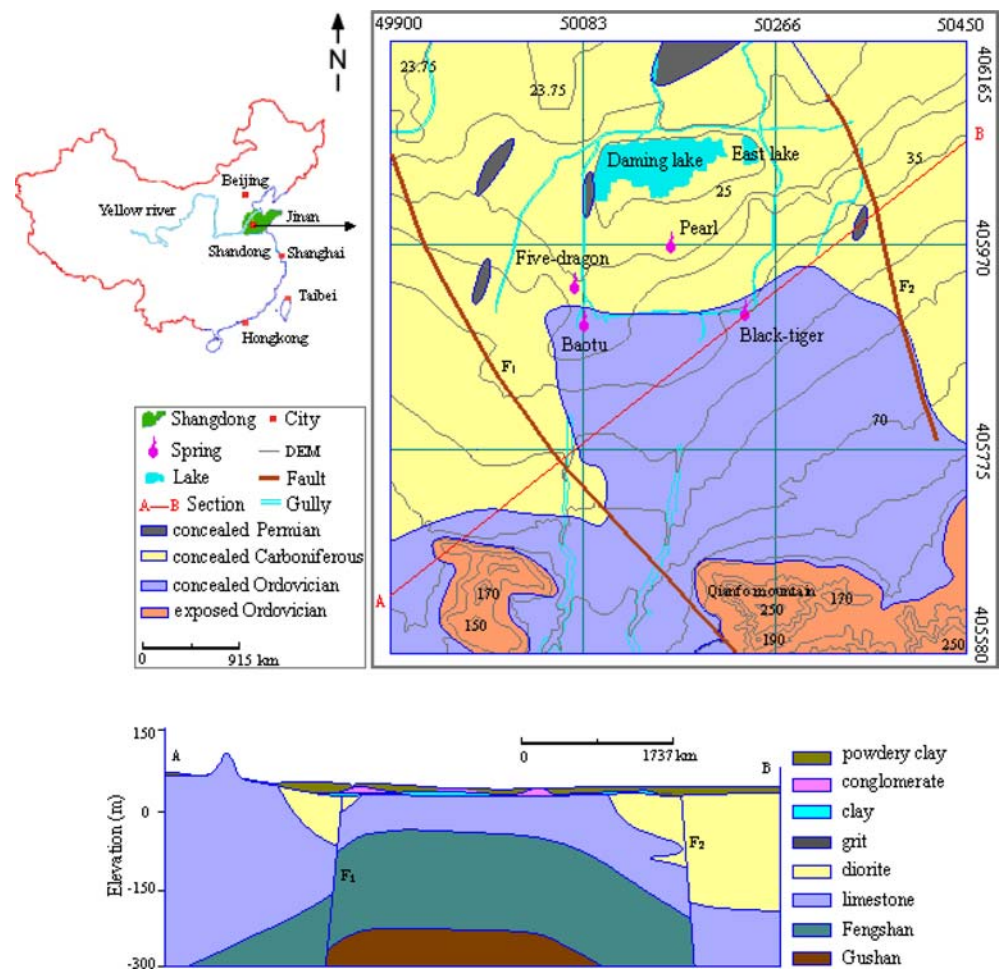**Fig. 1** Geology map with a cross section

Table 1 Data structures

Polygon	Double *Box* [4]	Integer *NumPoints*	Point *Points	Integer *Type*	Integer *Flag*
Line	Double *Box* [4]	Integer *NumPoints*	Point *Points	Integer *Flag*	
Point	Double *x, y, z*	Integer *Flag*			

consists of a triplet of double-precision coordinates in the order *x*, *y*, *z* plus a *Flag* as the property value of the point. A line is a connected sequence of two or more points, and a polygon is a connected sequence of four or more points that form a closed, nonself-intersecting loop. Vertices of rings defining holes in polygons are in a counterclockwise direction (*Type* = 0). Vertices for a single, ringed polygon are, therefore, always in clockwise order (*Type* = 1). The *Box* for the line and polygon is used to store in the order Xmin, Ymin, Xmax, and Ymax. The *NumPoints* is the number of points in the object.

For easy observation, only part of the result of the object-oriented integration in the Jinan spring area is displayed (Fig. 2). The borehole data and springs are regarded as point objects. Fault lines extracted from

structural geology maps are line objects. Cross sections and seismic data are line or polygon objects. In addition, geological boundaries extracted from geological maps, gullies, and lakes are polygon objects. They are all important geological information in the 3D modeling.

3D geological modeling

Fault simulation

Construction of the correct 3D fault geometric models is one of the crucial problems in modeling and visualization of the geological processes. Fault data, both original and those interpreted from boreholes and cross
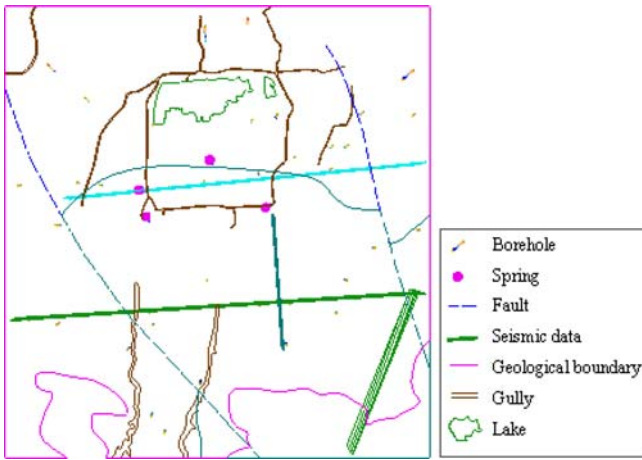
Fig. 2 Instances of object-oriented integration in the Jinan spring area

sections, are scarce in the Jinan spring area. It is not often feasible that the complicated geological structure in the area can be completely approximated by using only these data and the methods that are commonly used. According to the characteristics of the faults in the Jinan spring area, a modeling framework is presented that aims to establish an efficient fault model. The process mainly involves four steps: (1) determining the property parameters of faults, such as dip, direction, and displacement, and building a database of them; (2) digitizing the fault lines extracted from the structural geology maps, and converting them to the 3D modeling system through data transformation DCI; (3) importing the scatter fault points acquired from boreholes and cross sections, which is used as the base data for faults simulation; (4) deducing the geometry shape of the faults by applying the methodologies for the mathematical description and computer simulation of faults (Wu and Xu 2003). In order to simulate more realistic faults, some of the fault points are inserted or deleted by the interpolation or interactive operation (Fig. 3).
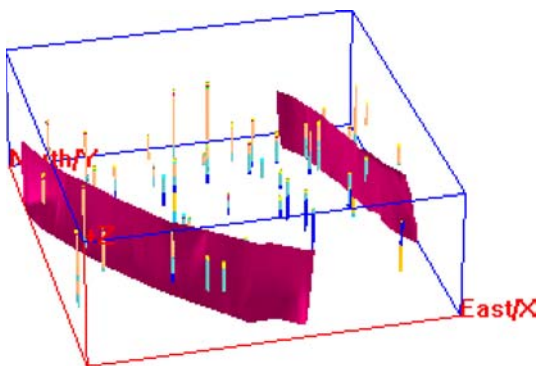

Fig. 3 Faults simulation with boreholes

Horizon construction

A 3D model depends highly on the construction of horizon models. It is important to improve the accuracy of the horizon models. For this purpose, the study is focused on the approaches to utilize the data of different types and qualities from the Jinan spring area. In this paper, we introduce a new method to generate an accurate horizontal model based on the existing sparse and irregular data.

The first step is to abstract the point, line and polygon objects from the multiple source data using the data integration technique described above. The topological and geometrical information of these objects are stored and managed by building a hierarchical link list. Considering the sparseness and irregularity of the spatial sampling in the Jinan spring area, a set of regular point objects are added into the corresponding link list with an interpolation technique (Joyce et al. 1997).

The next step is to create the mesh for each horizon using the constrained Delaunay triangulation (Conraud 1995; Shewchuk 1998), where the line and polygon objects, such as geological boundaries, lakes, and faults, are regarded as the constrained edges. To accurately represent the complicated geological and geographical conditions in the area, e.g., the Qianfo Mountain (Fig. 1), the coarse meshes are refined in the localization zone by the subdivision operation (Wu and others 2005).

The nine geological units as described above are successfully modeled by the proposed method. Figure 4 shows each corresponding horizon model constructed. We can observe the distribution of each stratum in the 3D space and calculate its thickness. Figure 4a, b, and c represent the models of powdery clay, conglomerate and clay of the Quaternary age, respectively, with the maximum thickness being 30 m. The grit of the Permian age is relatively thin in the area, on an average 3–4 m (Fig. 4d). The diorite of the Carboniferous age, a coal-bearing stratum, mainly distributes in the north of Jinan (Fig. 4e) and its thickness ranges from 100 m to 250 m. The limestone of the Ordovician age covers almost all of the study area (Fig. 4f). Figures 4g, h and i display the models of the Fengshan, Gushan, and Zhangxia Formations of the Cambrian age, respectively.

Solid representation

Several methods have been developed for defining the solid model. According to the characteristics of the geological data in the Jinan spring area and the application demand of the 3D modeling, the following three steps are followed to reconstruct a 3D solid.

1. Calculating the intersection points between both two horizons, and between horizons and faults.

Fig. 4 Horizon models
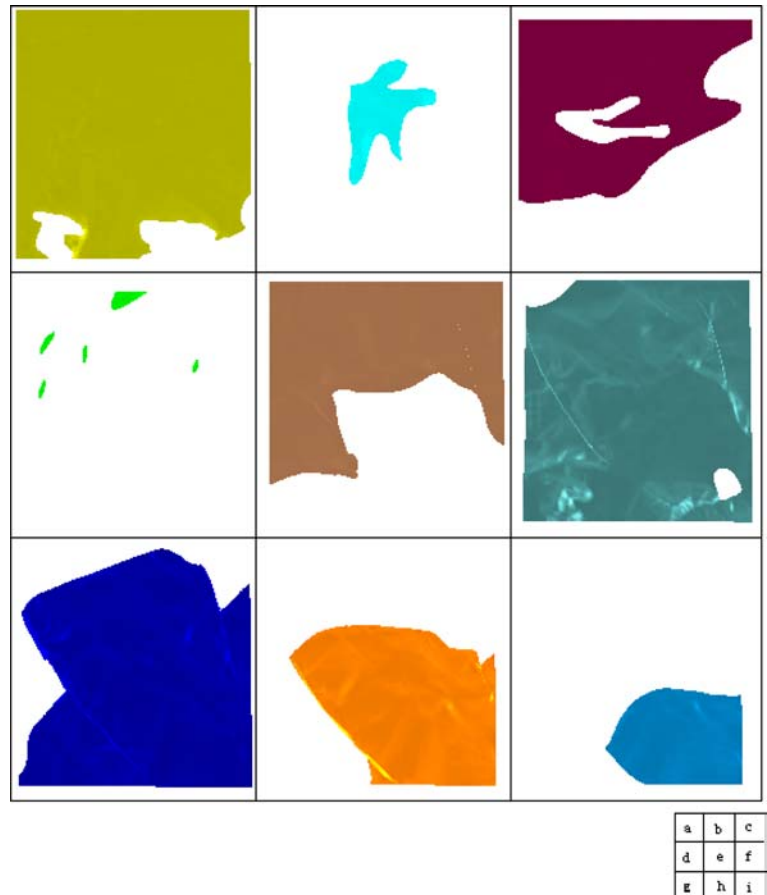
2. Reconstructing the mesh.
3. Establishing a Boundary representation (B-rep) solid model by the topological relationship between faults and each horizon surface.

As representation or simulation of the surface water, groundwater, and other natural phenomena in the spring protection requires the use of 3D meshes, the

Fig. 5 A 3D model in the Jinan spring area

system has provided the option to build tetrahedron networks or 3D grid models from B-rep solid models. Figure 5 represents a 3D model in the Jinan spring area. We can zoom, move, strip, and rotate this model. Space analysis and space query can also be performed in the model.

Water resource simulation

Once the geological modeling process is completed, the model is used for the water resource simulation in the Jinan spring area. The most famous four spring groups, named Baotu, Black-tiger, Pearl, and Five-dragon, consisting of more than 100 springs, are added into the model (Fig. 5).

For the simulation of surface water like gullies and lakes, a reliable, cost-efficient approach has been proposed in the paper. Two issues, reconstruction of horizons and simulation of water flow, should be considered.

To locally reconstruct the horizon models, let us define R as the set of points to describe a gully or a lake while ∂R as the boundary of R. For any point p that is in the exposed area of the horizons, if p falls into the area
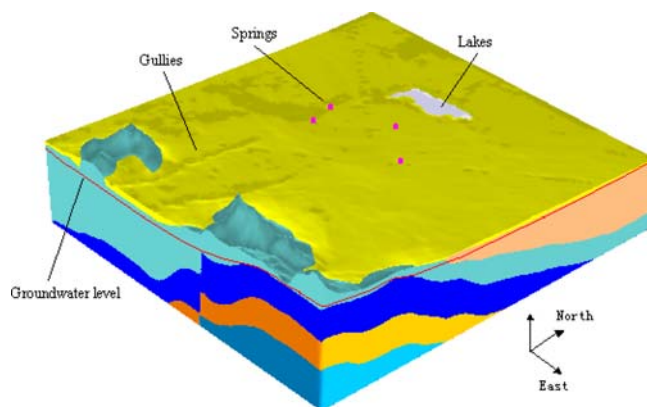
∂R, the interpolation to p is performed using the points in R as known samples with kriging. In fact, the result of the interpolation to these points further improves the accuracy of the 3D model to provide the most reliable surface-water simulation. For instance, the surface of the Quaternary powdery clay model is relatively smooth before reconstructing (Fig. 4a). However, after reconstructing the model, some concave areas appear (Fig. 5). These concave areas are used to simulate the bottom of gullies, lakes, and natural features. The dynamic simulation of water flow is performed based on the particle system and water level fluctuations, similar to the works performed by Nathan and Burkhard (2003) and Zacharias et al. (2003).

In comparison with the surface water simulation, development in the simulation of groundwater levels involves itself only. A groundwater level can be expressed in a surface displayed in 3D space. The interpolation is first made on the contours of the water table calculated, and then a triangle irregular network is generated using Delaunay triangulation to simulate a groundwater level. For example, Fig. 5 shows a groundwater level between 20 m and 42 m elevation in the Jinan spring area in June 1990. It reflects the change of water level under the low-flow conditions in the spring area.

Results and discussion

Once a coherent 3D model is developed, we can visualize the model from various perspectives, present isolated horizons, cut fence diagrams, calculate cross sections, generate contour lines, perform statistic analysis, and search for information. Figure 6 shows some of strata, e.g., the karst aquifer and the diorite that may be directly related to the water flow at the springs.

The remote sensing image was also mapped into the 3D model using the texture techniques to provide more useful information (Fig. 7 and 8). For easy observation
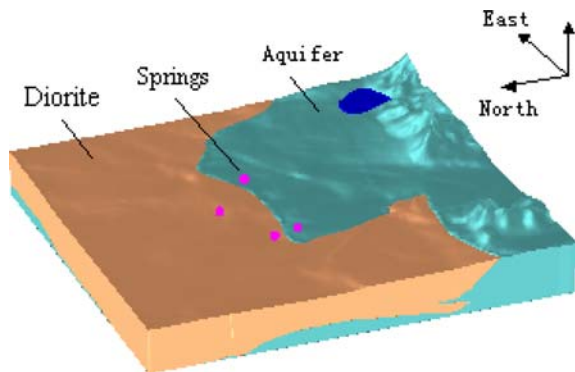
and analysis, we have applied this user-centered approach to data visualization by using a virtual environment to create an interactive 3D scene (Fig. 7). A fast algorithm is designed to calculate and display the real-time cross sections with groundwater levels. An example is shown in Fig. 8. Additional data can also be integrated within the 3D model, such as borehole data or specific horizon properties, e.g., hydrochemical parameters. The information on the precise underground geometry provides a basis for the development of the Jinan springs.

As can be seen from Figs 5, 6 and 7, the Jinan springs occur because of the unique geologic conditions. The Ordovician limestone is a water-bearing stratum in the spring area, and is exposed on the ground surface in the south. The topography in Jinan is higher in the south than in the north. Spring water comes from the mountainous area of the south. The more than 260-m elevation difference between south and north makes the surface water and groundwater flow northward along the stratum and then is blocked by the impermeable diorite.

Consequently, the spring water discharging from the crevices among the rocks helps maintain a certain groundwater level in the aquifer. In other words, there could be enough water in the spring area to keep a certain groundwater level. According to testing data from the Baotu Spring (Meng 2003), which is known not only as the largest one in Jinan but also as one of the four famous springs in China, the threshold groundwater level to maintain the spring flow is 26.98-m elevation. Baotu Spring will flow, if the groundwater levels reach the value. Figure 9 shows the contours of the water table calculated in June 1990, as well as the relationship between a simulated groundwater level based on the contours and the aquifer. The elevation of groundwater level around the spring groups is 20–21 m. It is likely that the Jinan springs stopped flow during that period.

The reasons to cause the dry up of the springs are water and soil erosion and groundwater overexploitation. The water and soil erosion in the upper reaches of the spring area is especially serious. Many factors contribute to the water and soil erosion, including the unscientific cultivation and deforestation. The mountainous area in
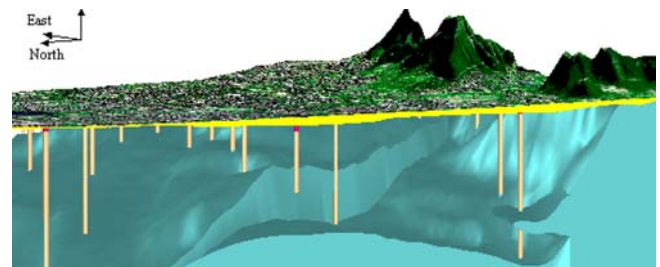

Fig. 6 Strata related with the cause of the springs

Fig. 7 Aboveground and underground in a virtual environment

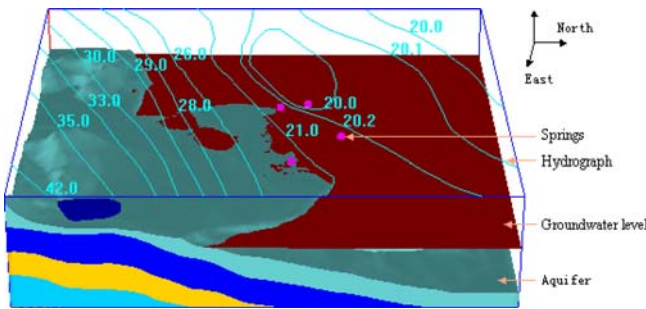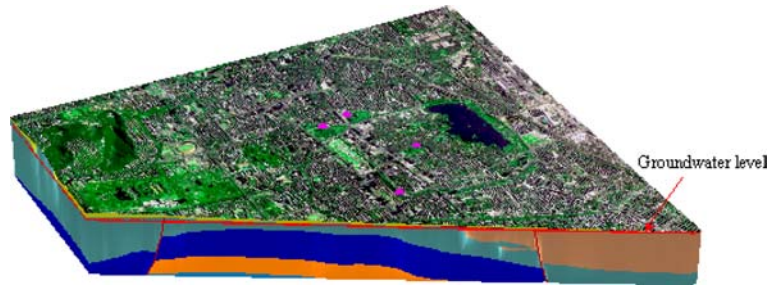**Fig. 8** A cross section calculated with a groundwater level

Fig. 9 A groundwater level with related strata

the south is the main source for the Jinan spring water. The recharge area of the springs covers 1,500 km^2, which comprises 550 km^2 of direct recharge area and 950 km^2 of indirect recharge. Both of them are in the mountainous area in the south. The remote sensing image analysis indicates that the forest coverage rate is lower, and the ecological situation tends to get worse in the mountainous area in the south (Figs. 7 and 8). The increase of the impermeable area and decrease of the cultivated land and vegetation cover have resulted in a significant change of the surface conditions in recent years. This change influences the rate and volume of the rainfall run off, and leads to reduction of the amount of groundwater available in the spring area. The result of the simulation shows the severe groundwater overexploitation in the lower reaches of the spring area (Figs. 8 and 9), which poses a major threat to the water ecosystems. The expansion of Jinan City, coupled with the rapid population growth and the even faster growing consumption of water, means an increased demand for water.

The detailed 3D simulation provides more definitive data for analysis of the cause of the spring depletion, which helps regional planning and policy making. This study also provides a base for further study focusing more on 3D numerical simulation of groundwater flow in the spring area. The advantage of this study is the ability to show prospective results of a future design, e.g., the change of groundwater level while pumping water at a virtual well without additional development costs.

Conclusions

This study was motivated by the fact that the Jinan springs have not been properly protected even after the government has invested much more resource since 1980s. It seems that it is difficult to achieve the goal of the spring protection by the method commonly used. The 3D modeling, in association with the environmental geography, GIS, groundwater modeling system, remote sensing, computational geometry, data mining, visualization, and virtual reality, is used in this study. It aims to provide decision supportive information to policy makers in formulating appropriate strategies; to the academe, a shared platform; and to present the general public with the updated and visual information.

The following conclusions can be drawn from this study:

1. The data integration technique proposed in this paper can enhance the accuracy of the 3D modeling. The case study showed that the integration of the MS Access, Oracle, AutoCAD, ArcView GIS or other interpretative software could result in a useful 3D model from the geological data of different types and qualities from the spring area.
2. The study analyzed the geologic conditions, which favor the formation of the Jinan springs, and the cause of the springs' dry up by the 3D geological modeling, as well as the surface and groundwater simulation. It provides a better understanding and quantitative evaluation of the structures of the aquifer.
3. The sophisticated 3D simulation provides for the first time the necessary visual accuracy to make assessments quickly with minimum financial outlay. It is a valuable tool for policy makers to develop effective and practical strategies for the spring protection.

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