3D MODELING OF GROUNDWATER BASED ON VOLUME VISUALIZATION TECHNOLOGY

Xu Zhiyong [a,b], Zhu Guorui [a,b], Wu Xiaofang [a,b] and Yan Huiwu [a,b]

[a] School of Resources and Environment Science, Wuhan University, Wuhan, China
[b] Key Laboratory of GIS, Ministry of Education, Wuhan, China—XuSirZY@163.com

KEY WORDS: Volume Visualization, 3D Model, Interpolate, 3D Profile, Groundwater, Inverse Distance to a Power

ABSTRACT:

Water Resource is one of the most important nature resources, and it is the strategic resource for economic development. With the development of industry and agriculture, city population increasing, more and more water is needed, as well as the groundwater. It causes the groundwater over-extraction, and a series of serious environment problems such as region's groundwater cone of depression, land subsidence, seawater inbreak, water quality deteriorate. It is very necessary for us to study groundwater resource.
Traditionally, 2D data model is used and 2D planes and slice are represented the result, not the true 3D, so it is difficult to analyse groundwater resource exactly. Therefore, Volume visualization technology is introduced into the field of groundwater resource.Volume visualization technology is that scatter sampling in finite space, each value of sampling point will be one or more properties, which represent its physical property. So it is very suitable to represent the true 3D geo-phenomena, such as the existent condition of groundwater, the groundwater cone of depression and the groundwater effluent seepage field. This paper researches how to represent the time-space distribution and dynamic change characteristic of hydrogeologic layer and its inner physical and chemical attributes, such as intrinsic permeability, porosity, water quality, groundwater temperature and so on, groundwater effluent seepage field moving regulation, represent the development procedure of groundwater cone of depression. Thus it provides the scientific foundation of decision support for the extraction of groundwater. Central contents including: 3D modelling of existent condition of groundwater, 3D modelling of groundwater effluent seepage field and spatial data probe.

1. INTRODUCTION

Groundwater is the water which lies in the pole of rocks under the ground, and it can′ t be observed directly. Only by means of the hydrogeologic reconnaissance and groundwater dynamic monitoring, we can disclose the existent condition and moving rule of groundwater. However, owing to the limitation of reconnoitering money, the density of hydrogeologic reconnaissance well is limited, so we can′ t directly gain the information of hydrogeologic volume between the reconnaissance wells and only gather the information by the experience of hydrogeologic worker. Then there are more errors in recognizing the hydrogeologic condition and there are blind-areas in the hydrogeologic condition information, and at last it will have an ill effect on the veracity of the hydrogeologic research result. Therefore, how to use the present scientific technique to show the existent condition of groundwater, moving regulation and dynamic characteristic, disclose the hydrogeologic condition of evaluation area completely and accurately and provide the scientific foundation for the hydrogeologic research, becomes one of the urgent studying subjects in the present hydrogeologic field.

The research task lies in the research fields of 3D geo-modeling in nature. The methods of traditional 3D geo-modeling include the digitized modeling and geometric modeling. The digitized modeling can describe the attribute of inner physics and chemistry in the geologic body well, but have difficult in describing the spatial shape of the geologic body. But, the geometric modelling takes advantages of describing the spatial shape.Therefore, the regular method is to synthesize the digitized and geometric modeling in the research of 3D geo-modeling. It is to represent the attribute of the geologic body by digitized modeling and describe the spatial geometric shape of the geologic body by geometric modeling. Then, the present important research problem is to construct one model which can not only describe the spatial geometric shape of the geologic body, but also represent the inner physical and chemical attribute and avoid the problem of separation between the spatial geometric shape and inner attribute in the geologic body. The basic thought is to use the technique of volume visualization to construct and show the hydrogeologic layer and its inner physical and chemical attributes such as intrinsic permeability, porosity, water quality, groundwater temperature field, and apply the hybrid volume-rendering technique to represent the time-space distribution and dynamic change characteristic. Thus it proposes the scientific foundation of decision support for the extraction of groundwater , the pollutional monitoring of groundwater, and the management of groundwater.

In the paper, the research area is Chang Zhou—Wu Jin district where the phenomenon of the groundwater over-extraction and groundwater cone of depression and land subsidence is more serious. The research region of the groundwater resources is very large, so its macroscopical characteristic and nature of trend analysis are very remarkable. To study 3D visualization of the groundwater resources, the author divides the groundwater 3D data into two classes: scalar field and vector field. Section 2 focuses primarily on the 3D modelling of scalar field. 3D modelling of vector field will be discussed in the section 3.Section 4 analyses the research result, and then proposes the method of spatial data mining. And finally, conclusions are given in section 5.

2. 3D MODELLING OF EXISTENT CONDITION

2.1 Introduction

In hydrogeologic field, the data resource is the documentary data from probing and boring. Firstly, the geometry model is built from the data, Then, the volume data is gained by voxeling the geometry model, which is implemented by mathematic interpolate.

The data of hydrogeologic scalar field can be generalized as three hydrogeologic phenomena: one is the phenomenon of homogeneity change characteristic, the other is the phenomenon of horizontal change characteristic, the third is the phenomenon of 3D change characteristic. The data of these phenomena are scattering. Therefore, the method of improved inverse distance to a power is applied to building the 3D volume model of hydrogeologic scalar field by interpolating.

In the paper, the inverse distance to a power is introduced, its shortage is analysed, and this method is improved. Finally, it is applied to 3D modelling of three phenomena of hydrogeologic scalar field.

2.2 The Improved Inverse Distance to a Power

2.2.1 Base Principle of Inverse Distance to a Power

Inverse distance to a power is put forward by the researcher of aerography and geognosy, later it is named after Shepard. The base thought is: supposed spatial point sets $\{(x_i, y_i, z_i) \mid i = 1, \cdots\cdots, N\}$, the projection of point (x_i, y_i, z_i) in x-y plane is (x_i, y_i) , named D_i. The z value of any point $P(x, y)$ in plane is influenced by the z_i in D_i. But, the influence of z_i is oppositive to the distance between z_i and z.

z_i is the z value of $D_i(x_i, y_i)$, $d[P, D_i]$ is the distance between P and D_i , $d[P, D_i]$ can be abbreviated as d_i 。 The Z value of point P is represented by formula (1)：

$$f(P) = \begin{cases} \dfrac{\sum_{i=1}^{N} (d_i)^{-\mu} z_i}{\sum_{i=1}^{N} (d_i)^{-\mu}} & d_i \neq 0 \text{ for each } D_i \\ z_i & \text{When } d_i = 0 \end{cases} \tag{1}$$

μ is the exponent and should be more than zero, is very important to the result. Figure1 is the result graph of μ =0.5,1.0,1.5,2.0,5,20.Certainly, when μ =2.0, the result is the best, and operation speed is the fast because it needn't extraction of root.

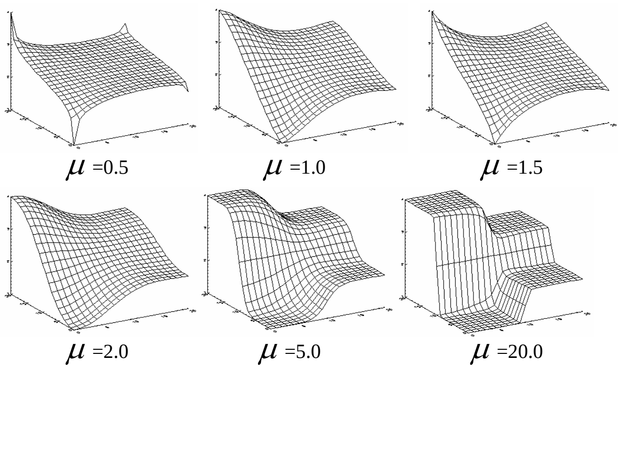

Figure 1. different interpolated surfaces based on inverse distance to a power

From the formula 1, we can see that inverse distance to a power is very simple and nature, but it has many shortcomings:

(1) When the number of point is very large, the calculation of $z = f(P)$ is very huge and difficult.

(2) It consideres only the influence of distance, not the direction. Sometimes, the direction is very important for interpolation.

(3) The surface is not limited by derivative in each known point.

(4) when $d_i \approx 0$,the calculation is very difficult because the error is very sensitive, especially denominator is close to zero.

Each of the shortcomings can be revised. Firstly, Selecting neighbour points can solve problem 1 and 2, and then problem 3 can be revised by estimating derivative, at last, reducing calculation error can solve problem 4.

2.2.2 Select Neighbour Points

From the formula 1, we can see that only the points near by P are important when calculating the z value of P. The points, which are fast away from P, have very litter influence to P. So the calculating time can be saved if only the points near by P are used in formula 1.

Voronoi is good tool for representing the vicinity relationship. So voronoi is used to get the neighbour points of P. And, the neighbour points of P are classified, each class has different influence on P. When building the voronoi map, the neighbor of P is named Class-First-Neighbor-Point(CFNP), the neighbor of CFNP is Class-Second-Neighbor-Point(CSNP), and then the Class-N-Neighbor-Point can be gained.

Obviously, the influence of CFNP is larger than CSNP. The experiment shows: Both linear model and exponential model from CSNP to CFNP can represent the influence degree. Generally, the class number of neighbor select two.

Let neighbor of p is $C_p^{'}$ (or $C^{'}$). if the neighbor degree is considered, new weight function is $W_i = (d_i)^{-2} w_i$, the z value of P is as follows :

$$f(P) = \begin{cases} \dfrac{\sum_{D_i \in C^{'}} W_i z_i}{\sum_{D_i \in C^{'}} W_i} & d_i \neq 0 \text{ for each } D_i \\ z_i & \text{When } d_i = 0 \end{cases} \tag{2}$$

2.2.3 Estimate Derivative

It is a character of inverse distance to a power that the grads of each point is zero. A little increment adds to the parameter z_i in the formula 2 on the vicinity of each point. So the surface has reasonable derivative on each point of D_i. Firstly, derivative is displayed by difference on both X and Y direction.

$$A_i = \frac{\sum_{D_j \in C_i^{*}} W_j \dfrac{(z_j - z_i)(x_j - x_i)}{(d[D_j, D_i])^2}}{\sum_{D_j \in C_i^{*}} W_j} \quad B_i = \frac{\sum_{D_j \in C_i^{*}} W_j \dfrac{(z_j - z_i)(y_j - y_i)}{(d[D_j, D_i])^2}}{\sum_{D_j \in C_i^{*}} W_j} \tag{3}$$

$$\Delta z_i = [A_i(x - x_i) + B_i(y - y_i)]\frac{v}{v + d_i} \tag{4}$$

The character of expression $v/(v+d_i)$ is just as d_i^{-1}. The result of expression is decreased from 1 to 0 monotonously with d_i from 0 to the larger value, which can control the influence of long distance point. But it is possible that the extent of Δz_i is very large. So v is formulated as follows:

$$v = \frac{0.1[\max\{z_i\} - \min\{z_i\}]}{[\max_i\{(A_i^2 + B_i^2)\}]^{\frac{1}{2}}} \tag{5}$$

It can be sure that:

$$|\Delta z_i| \le 0.1[\max\{z_i\} - \min\{z_i\}] \tag{6}$$

Obviously, the derivative of D_i :

$$\left.\begin{aligned} \frac{\partial}{\partial x}(\Delta z_i)\bigg|_{\substack{x=x_i\\y=y_i}} &= A_i \\ \frac{\partial}{\partial y}(\Delta z_i)\bigg|_{\substack{x=x_i\\y=y_i}} &= B_i \end{aligned}\right\} \tag{7}$$

This is the result that we need.

$$f(P) = \begin{cases} \dfrac{\sum_{D_i \in C'} W_i(z_i + \Delta z_i)}{\sum_{D_i \in C'} W_i} & d_i \neq 0 \text{ for each } D_i \\ z_i & \text{When } d_i = 0 \end{cases} \tag{8}$$

2.2.4 Reduce calculation error

when p is near by some of D_i, rounding or truncation will bring on large error. So, the ε vicinity of D_i is built.

$$\lim_{P \to D_i} f(P) = z_i \tag{9}$$

If p is in some ε vicinity, let $f(P) = z_i$. If p is in ε vicinity of many points, $f(P)$ equals the average z value of these point. Supposed $N(P)$ as these point set, the following is the last improved formula.

$$f(P) = \begin{cases} \dfrac{\sum_{D_i \in C'} W_i(z_i + \Delta z_i)}{\sum_{D_i \in C'} W_i} & d_i \neq 0 \text{ for each } D_i \\ \dfrac{\sum_{D_i \in N(P)} z_i}{\sum_{D_i \in N(P)} 1} & \text{When } d_i = 0 \end{cases} \tag{10}$$

2.3 3D Modelling of Scalar Field

2.3.1 Phenomenon of homogeneity change characteristic

The spatial distribution of hydrogeologic layer has generally the layered distributing character. On the vertical direction, hydrogeologic layer is divided into several different layers (such as aquifer). There is a typical interface between the layer and neighboring layer. And the inner of every layer is homogeneity. Therefore the spatial distributing structure of hydrogeologic layer is set up by building the model of interface between the layers.

There are four steps in setting up the architectural model of hydrogeologic layer as follows. Firstly: boundary interpolate. It is to add a serial of control points on the boundary or out of the research region so as to research the spatial distributing regulation of hydrogeologic layer well in the research region. The boundary points is always generated by the means of improved inverse distance to a power. Secondly, the improved inverse distance to a power is used to generate the bottom surface of hydrogeologic layer. Thirdly, the bottom surface is overlayed in order of the hydrogeologic layer, then the surfaces are pruned in terms of the incision and stagger relations between the surfaces, and the 3D geologic model of hydrogeologic layer is formed. At last, unite the 3D geologic model of hydrogeologic layer by stitching the top surface and the bottom surface, or build the cube model by interpolating (Nalder and Wein, 1998).

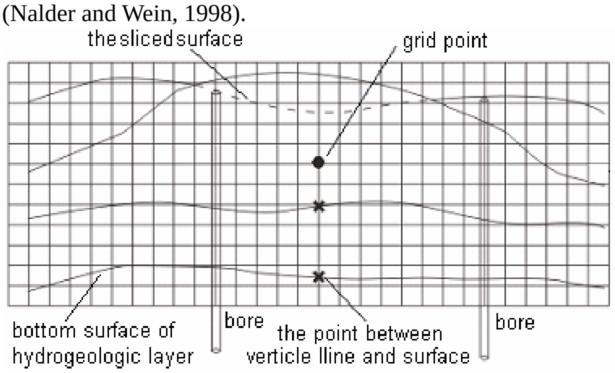

Figure 2. 3D model of phenomenon of homogeneity change characteristic

2.3.2 Phenomenon of horizontal change characteristic

Strictly speaking, the porosity, water quality, pondage rate, intrinsic permeability, and feedwater degree are the continual changing geo-phenomena in 3D space. In order to gain the geologic information, firstly get the rock core by bore, then analyze the rock sample by the physical and chemical experiment. Every bore just records one sampling value of certain geologic layer, which takes the sampling value as the attribute describing of one level position in rock layer.

The spatial distributing character of the horizontal geo-phenomenon is not changed in the vertical direction, but continually distributes in the horizontal direction. Therefore, the value of any point in the hydrogeologic layer is generated by interpolate algorithm, and the layered model is built, then the volume model of the whole region is formed at last.

In the paper, the scope of sampling data in the research region is taken as the bound box of volume model. The bound box is divided into NX×NY×NZ. NX, NY, NZ are the grid num of the X, Y, Z directions. The interpolate of grid data is implemented by the interpolate algorithm of inverse distance to a power, then the 3D volume model is formed (Decencière Etienne and Meyer, 1998).

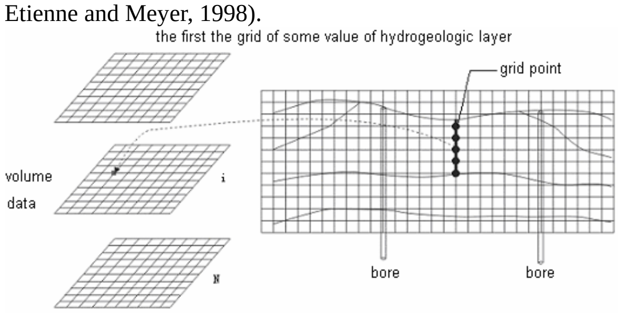

Figure 3. 3D model of horizontal change characteristic

2.3.3 Phenomenon of 3D change characteristic

The groundwater temperature and its physical and chemical attributes are the continual changing hydrogeologic phenomenon in 3D space. In the long time, the true 3D display and water temperature surveying of any position have great shortcoming because of the limit of surveying condition and visualization technology, which can be resolved by the volume visualization technology.

The spatial distributing character is 3D change characteristic which changes continually in the X, Y, Z directions. The essential of building the model is the 3D spatial interpolate (Deutsch, 1996).
The volume visualization efficiency of hydrogeologic layer and its physical and chemical attribute see Figure 4 below.

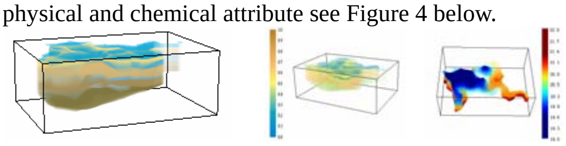

Figure 4. Volume visualization result of three phenomenon

3. MODELLING OF GROUNDWATER FLOW FIELD

In order to quantificationally analyze the groundwater resource of research region and control the geologic destroy efficiently, the groundwater flow field must be represented. It refers to two aspects (Hin and Post, 1993): One is to represent the development procedure of groundwater cone of depression in the aquifer, another is to represent the changing rule of the velocity of flow and the direction of flow with the change of time (Max et al., 1993).

At present, the numerical simulation technology is used to calculate the groundwater cone of depression, velocity and direction of groundwater flow. In the paper, the Changzhou city in China is selectd as the research region which lies in the downriver south side of Changjiang. See also Figure 5.

Figure 5. graph of the Ⅱ confined aquifer of research region.

The width of the region is about 55 km and its height is about 81 km. The structure of hydrogeologic layer is generalized into eight layers: diving aquifer, the Ⅰ waterproof layer, the Ⅰ confined aquifer, the Ⅱ waterproof layer, the Ⅱ confined aquifer, the Ⅲ waterproof layer, the Ⅲ confined aquifer, the Ⅳ waterproof layer. In this paper, the typical Ⅱ confined aquifer is taken as the research example, and the 3D mathematic model of groundwater flow of the Ⅱ confined aquifer is set up according to the equilibrium principle and Darcy law.

$$\begin{cases} \frac{\partial}{\partial x}(K_{xx}\frac{\partial H}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial H}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial H}{\partial z})+W=\mu_s\frac{\partial H}{\partial t} & (x,y,z)\in D \\ H(x,y,z,t)\big|_{t=0}=H_0(x,y,z) & \text{initial condition} \\ H(x,y,z,t)=\varphi_1(x,y,z) & AB \\ H(x,y,z,t)=\varphi_2(x,y,z,t) & CD \\ \partial H / \partial n = 0 & BC, DA \end{cases} \qquad (11)$$

K_{xx}, K_{yy} and K_{zz} are the penetrative parameters, their unit is LT^{-1}.

where H =water level (L)
W =flux per volume (T^{-1})
μ_s =feedwater rate of the multi-bore medium which represents the feedwater degree of inter space medium per volume when the water level depresses one percent.
t =time(T)
D =seepage region

This is a complex equation, which involves time and spatial factor. To Solve this equation, the derivative is displaced by difference, and the finite difference method is used normally. The famous groundwater simulative software: MODFLOW and the 3D finite difference method is used to do numerical solution about the above model. First the time and space dispersing section and difference functions is built, and the hydrogeologic conditions and parameters is manipulated, the SOR is used to gain the data of water level, water deep and water flux of the Ⅱ confined aquifer from 1999 to 2000, then the groundwater flow model of the Ⅱ confined aquifer is set up in the research region, at the same time, the value of scatting point of the water level in special time is gained, so the cone of depression model is generated by the means of boundary-confined DEM. Because the regular grid is used in the spatial dispersing and time is dispersed equal isometry, when the equation is solved, the volume data of flow field can be gain. Figure 6 is the result of groundwater cone , and Figure 7 is the Visualization of groundwater effluent seepage field.

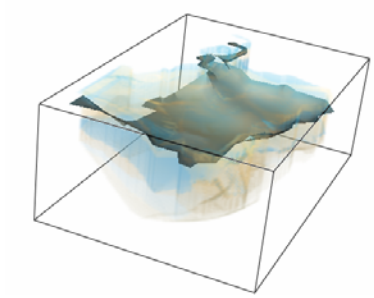

Figure 6. Groundwater cone of depression

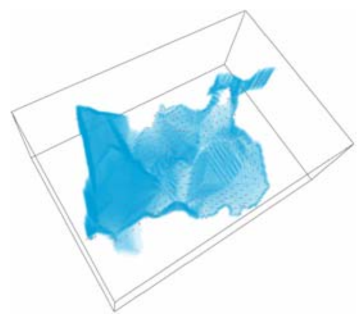

Figure 7. Visualization of groundwater effluent seepage field

4. SPATIAL DATA PROBE

In the research of groundwater resources, geological engineer need understand hydrogeological section of some aspect of direction, and then comprehensively research and realize it by much angles, find the hydrogeolical law. This is the typical space data probe.

The basic demand of space data probe is to obtain quickly some attribute information of any place. Obviously, it is a space interpolation problem, the improved inverse distance to a power, can be used to interpolate and get attribute information of any point. But, it is difficult for the users to picks the point by mouse, the slices of both any direction and any place are proposed by this section.

The method of slice on volume is that: many regular grid points are distributed on the selected plane, and the attributes of these points are gain by the interpolation based on the improved inverse distance to a power. Figure 8 is the flow field of certain slice.

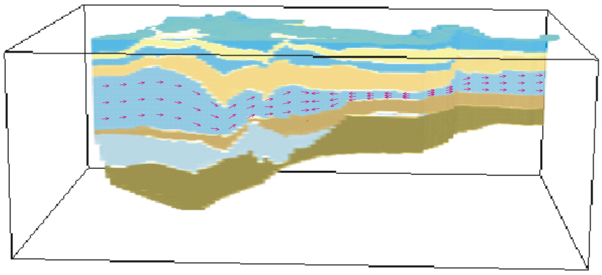

Figure 8. the flow field of certain slice

Considering the geographic map of research region, the result finds out that the center of the cone of depression mostly distributes in the region of developed industry and dense population along the Shanghai-Ningbo railroad. Therefore we can make a conclusion that the groundwater cone of depression is caused by the groundwater over-extraction. The field of the region depression is suitable for the field of the groundwater cone of depression in the Ⅱ confined aquifer. Therefore, we must control the groundwater extraction amount of the Ⅱ confined aquifer in order to avoid the worsen of the geologic disaster and environment.

5. CONCLUSION

In this paper, the improved inverse distance to a power is is used to build the 3D model of scalar field. Then the 3D flow model was built up based on the finite difference method. The space data probe is discussed in the paper. At last, the research result will help to understand and recognize the condition of groundwater and improve the research development of groundwater resource.

REFERENCE

Decencière Etienne, F.C. de and Meyer, F., 1998: Applications of kriging to image sequence coding. *Signal Processing: Image Communication* 13(3), pp.227-249.

Deutsch, C.V., 1996: Correcting for negative weights in ordinary kriging. *Computers & Geosciences Volume* 22(7), pp.765-773.

Griffith, D.A. 1983: The boundary value problem in spatial statistical analysis. *Journal of regional science* 23, pp.377-387.

Hin, A.J.S. and Post, F.H., 1993: Visualization of turbulent flow with particles. *IEEE Proceedings of Visualization′93*: pp.46-51.

Jimenez-Espinosa, R. and Chica-Olmo, M., 1999: Application of geostatistics to identify gold-rich areas in the Finisterre-Fervenza region. NW Spain. *Applied Geochemistry* 14, pp.133-145.

Klassen, R. and Harrington, S., 1991: A Technique for visualizing 2D slice of 3D vector field. *Proceedings Visualization'91*, IEEE Computer Society Press.

Max, N., Becker, B. and Crawfis, R., 1993: Flow volume for interactive vector field. *IEEE Proceedings of Visualization′93*: pp.19-24.

Nalder, I.A. and Wein, R.W., 1998: Test of a new method in the Canadian boreal forest. *Agricultural and Forest Meteorology* 92(4), pp.211-225.

Rosenblum, L.J., 1994: Research issues in scientific visualization. *IEEE Computer Graphics and Applications* 3, pp.61-85.