

An algorithm for the reconstruction and visualization of 3-D groundwater units

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Abstract This article presents an approach for characterization of the three-dimensional (3-D) shape and relationships of groundwater units by using data obtained from well logs. The methodology encompasses the following main steps, based on the input information generation of a set of images applying geostatistical simulation techniques. Each image contains a section from three different types of groundwater unit: impermeable, less permeable and permeable; enhancement of the quality of the images by a mathematical morphology approach; generation of three new sets of images by applying 5-D vector feature space defined over the numerical field with a given distance. Each set contains sections from one groundwater unit; each set of groundwater sections is divided into subsets of similar sections by 3-D vector feature space. Each subset presents a 3-D body belonging to a certain 3-D groundwater unit. In order to create 3-D surfaces an approach based on regularities and essential border points is applied. A software tool was developed on the basis of the methodology. Experiments were performed using data from Vale de Milhaços, Setúbal region, Portugal, .

INTRODUCTION

In order to study groundwater flow and contaminant transport it is very important to model the three-dimensional (3-D) shape of the aquifer and to define the relationships between different groundwater units such as: impermeable, less permeable, more permeable, and also the relationships between different bodies.

To enable better understanding of the flow and the movement of pollutants through aquifers in the vicinity of waste disposal sites it is necessary to have an adequate description of the aquifer heterogeneity in terms of the spatial distribution of the hydrostratigraphic units, because the continuity and the interconnectedness of these will influence the spatial patterns of the hydraulic conductivity and therefore determine the preferential pollutant pathways.

In recent times, research tools have been developed in order to incorporate soft information towards a more correct hydrostratigraphic architecture description. For this goal, Johnson & Dreiss (1989) used a non-parametric geostatistical approach for hydrostratigraphic unit interpretation. The first author also later provided a study concerning the analysis of the experimental indicator variogram of several hydrostratigraphic structures (Johnson, 1995).

On the other hand, Muge *et al.* (1997) used a coding system that incorporates three constructing levels: impermeable, less permeable, more permeable.

Furthermore, in the characterization of contiguity between stratigraphic units, the use of mathematical morphology tools helps the identification of important features.

As the next step, geostatistical simulation of the input data obtained generates a set of images by well logs. The images are used as input data to an algorithm for two-dimensional (2-D) object recognition, 3-D object separation and reconstruction. On the basis of the algorithm software is developed and tested.

The method of 2-D object recognition and 3-D object separation is based on N -dimensional finite vector feature space defined over a numerical field with given distance (Sirakov, 1997). Five-dimensional (5-D) vector feature space is defined in order to recognise all 2-D sections belonging to one groundwater unit. Thus the initial set of images is divided into three different sets: the set of impermeable, less permeable, and more permeable images.

It is well known that one groundwater unit may contain several different 3-D objects. 3-D vector feature space is defined in order to recognise the similar 2-D sections. By this method, each set of 2-D groundwater sections is separated into subsets of similar 2-D sections. Further, each subset is used to create one 3-D object. To build 3-D object surfaces an approach based on the work of Boissonant & Geiger (1993) and Geiger (1994) is used.

THE CASE STUDY

As a case study we considered a site located at the Setúbal Peninsula near Lisbon, named Vale de Milhaços, where there are two waste disposal sites. The aquifer is unconfined and is one of the units of the Miopliocene groundwater system of Tejo; it extends over an area of 35 km². From the lithological point of view it consists of sand, silt sands, gravel, sandstones and clays associated in an interbedded architecture with a total average thickness of 100 m. Topographic gradients are about 4% and 8% to the southwest.

Hydrogeologically we can consider it a high permeability area, with well productivities of around 2 to 20 l s⁻¹.

The logs of 84 boreholes were discretized into 1 m intervals to a maximum depth of 70 m, giving 5809 data locations. According to a lithological classification criterion we have assigned an indicator value to each location as follows: *indicator 1* – impermeable; *indicator 2* – less permeable; *indicator 3* – more permeable. The indicator values for the three facies are 0.272, 0.198 and 0.530, respectively.

CONDITIONAL SIMULATIONS

Conditional simulations were performed using two different models: the mosaic model in which the two conditional probabilities are supposed to be independent of the distance, thus enabling the separate kriging of the indicators (cokriging of the indicators is reduced to their separate kriging), and the indicator residual model in which the residuals calculated by Muge *et al.* (1997) are supposed to have the same property.

Using the above models we have simulated the three indicators separately in a 20 × 100 × 0.5 m grid of the waste disposal sites area (hereafter called the local area, Fig. 1), giving a total of 210 000 locations.

For the calculations we have used the SISIM software, a sequential indicator simulation algorithm from the GSLIB package (Deutsch & Journel, 1992).

Figure 1 shows six simulated cross sections of the area under study obtained by the indicator residual model. The distance between sections is 100 m. In order to enhance the quality of the images mathematical morphology operators are used.

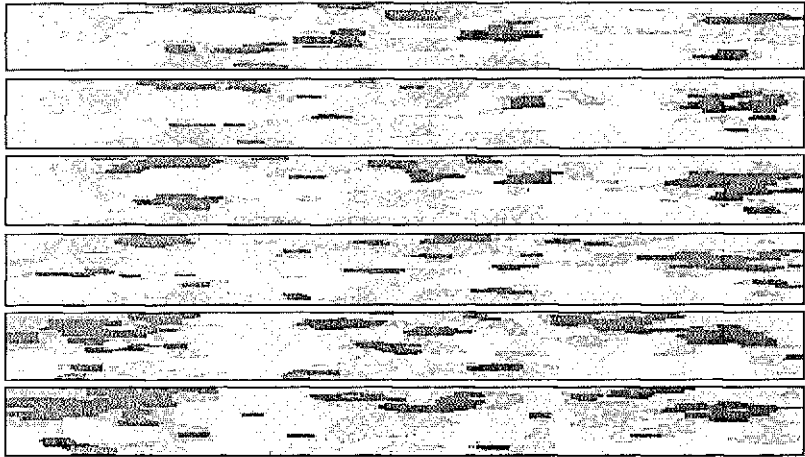


Fig. 1 Six simulated images containing impermeable (black), less permeable (dark grey), permeable (light grey) 2-D sections. The size of each layer is 5000×70 m (vertical exaggeration $\times 40$ m). The total thickness of each layer is 100 m.

RECOGNITION OF 2-D GROUNDWATER SECTIONS

To solve the recognition problem a 5-D vector feature space is constructed by using the N -dimensional case developed by Sirakov (1997). The following groundwater unit features are considered as vector components: lithological facies; grey-scale level (the different units have different grey levels); continuity; connectivity; inclusions. In the 5-D vector feature space each 2-D section is presented as a point. When the values of each feature are given, the space is defined over a numerical field with a given distance norm. Thus each 2-D unit's section will be the centre of a 5-D polyhedron. One 2-D section is considered similar to another one if it belongs to the corresponding polyhedron. Therefore the set of all the 2-D sections is divided into subsets of similar 2-D sections. Each subset contains 2-D sections from the same groundwater unit: set of impermeable – IP; set of less permeable – LP; set of more permeable – MP. On the base of this theory a software tool was developed. The results obtained when we apply this tool to the set of images shown in Fig. 1 are presented in Figs 2 and 3.

3-D GROUNDWATER OBJECTS SEPARATION

Note that one groundwater unit may contain different 3-D objects. The idea described above is applied in order to recognise and separate these objects. To do it 3-D vector feature space is considered. The components of this space are the following: the distance

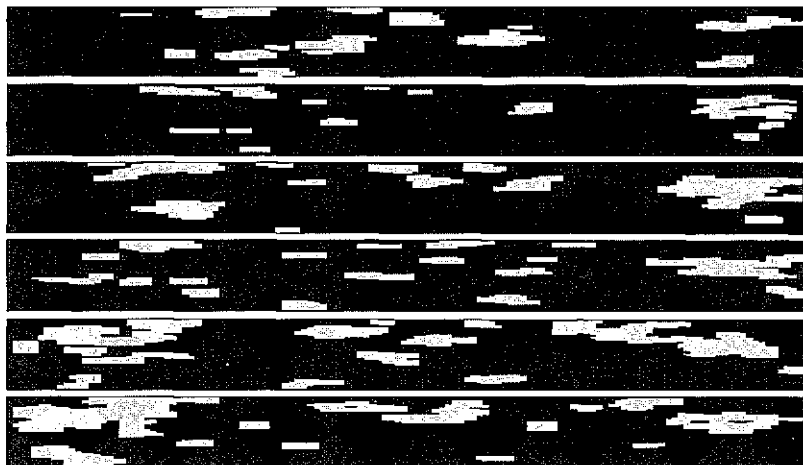


Fig. 2 The separated 2-D sections from impermeable units are presented in grey. See Fig. 1 for the size of the layers.



Fig. 3 Separated 2-D sections of the union between the less permeable and impermeable units are presented in grey. See Fig. 1 for the size of the layers.

between the different objects; the similarity of object borders; and, the number of essential points (Sirakov & Muge, 1994). In this space the sets IP, LP and MP will be separated to subsets of similar 2-D sections. Each subset constructs one 3-D object, which belongs to a fixed groundwater unit.

The results obtained applying the 3-D case over the sets of 2-D sections shown in Figs 2 and 3 are presented respectively in Figs 4 and 5.

Figures 4 and 5 show the relationships between the 3-D objects belonging to the impermeable and to the less permeable units, respectively. The relationships between impermeable and less permeable units are shown in Fig. 6. Straight lines link the similar 2-D groundwater sections, which are shown in the same shade.

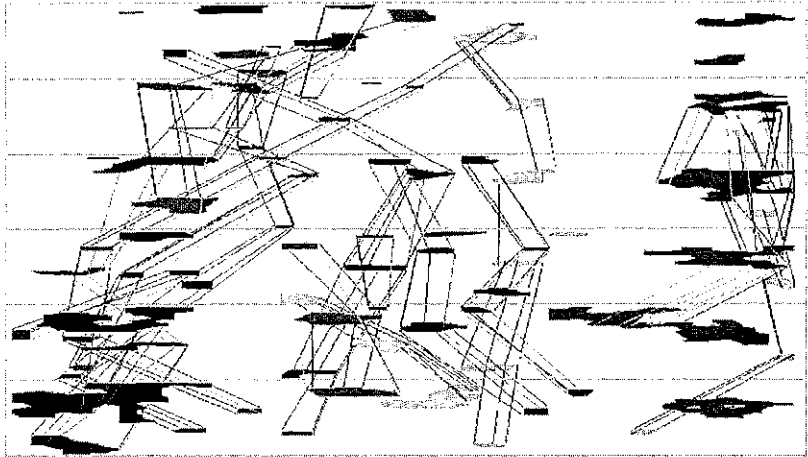


Fig. 4 The set of impermeable 2-D sections is separated to subsets of similar sections.

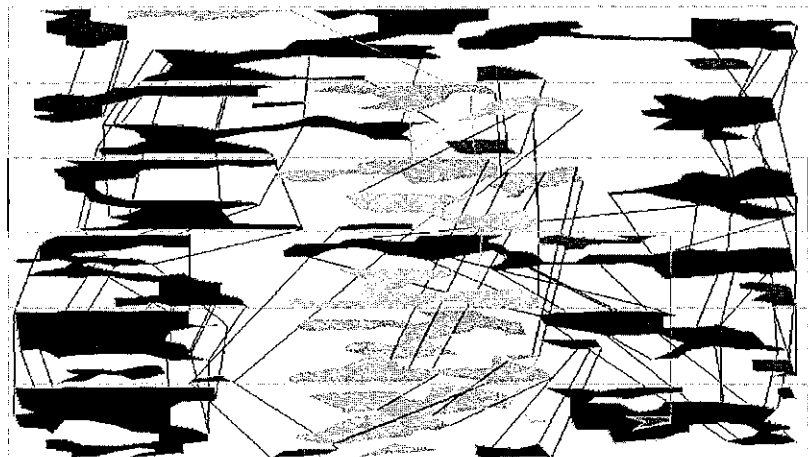


Fig. 5 The set of less permeable 2-D sections is separated to subsets of similar sections.

RECONSTRUCTION AND VISUALIZATION OF AQUIFER SURFACES

For solving the reconstruction problem an approach based on Voronoi diagrams, Delaunay triangulation (Boissonat & Geiger, 1993; Geiger, 1994), regularities and essential points (Sirakov & Muge, 1994) was developed. On the basis of the theory, a software tool was developed.

Figure 4 shows that too many different 3-D groundwater objects, with very complicated relationships exist there. On the other hand some 2-D sections are isolated since they are not similar to any other one. The isolated sections are not considered for the reconstruction. The result of the reconstruction of the different 3-D impermeable objects is presented in Fig. 7. In order to provide better visualization, the relatively small 3-D objects, and those 3-D objects, which for the most part are hidden since they are situated behind the other objects, are not shown in Fig. 7.

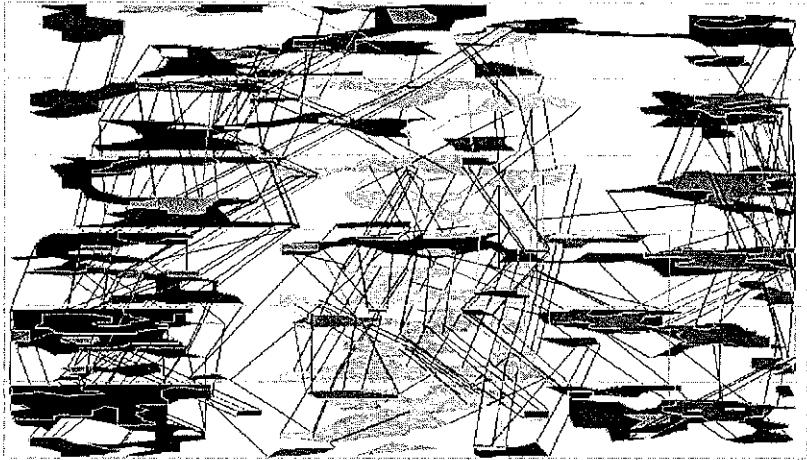


Fig. 6 3-D relationships between impermeable and less permeable units. See Fig. 1 for the size of the layers.

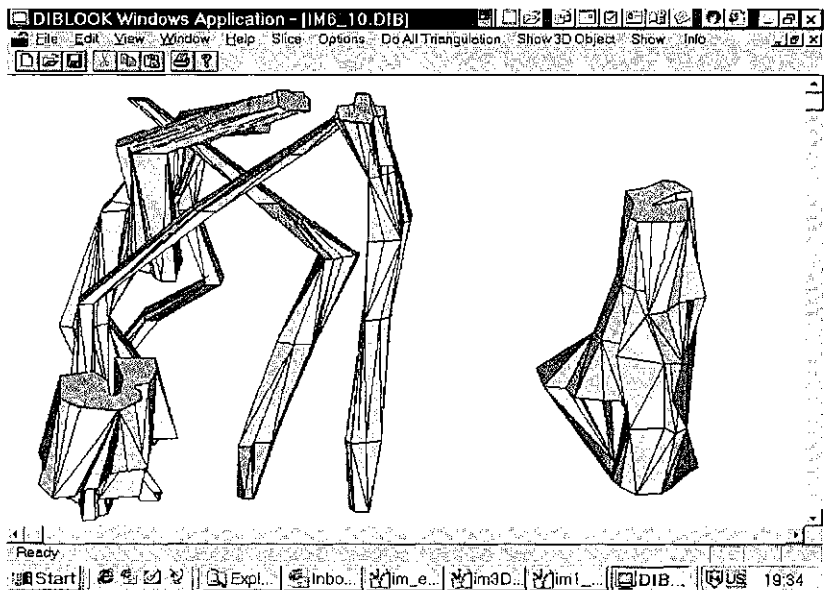


Fig. 7 3-D reconstruction of impermeable units and relationships between them. The size of the reconstructed subsurface area is $5000 \times 70 \times 600$ m.

Note that the results of recognition and reconstruction depend on the values of the space components, which may be chosen by a groundwater expert.

ADVANTAGES

The advantages of applying the present approach may be summarized as follow: the methodology and software tools enable generation of 2-D images and provide 3-D visualization of groundwater units using input data obtained by well logs; the

recognition tool enables separation of different 3-D objects and allows one to deal with them separately as different groups. The tools developed are directed at groundwater experts.

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