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3D Hydrogeological Modelling with an Expert GIS Interface

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Geographical Information Systems provide a powerful tool for creating three-dimensional (3D) datasets for sophisticated hydrogeological models. The article describes a GIS with an expert system interface developed for generating 3D hydrogeological frameworks. The system integrates 2D images of elevation and geology and vertical profile data. Application of the expert GIS to a complex aquifer in South Eastern Sweden is described.

Introduction

The quantity and quality of groundwater resources are increasingly threatened by *e.g.* over-exploitation and contamination. Predicting the subsurface movement and balance of water and contaminants are complex problems (*cf.* Konikow and Mercer 1988). Generally, the solution of these problems requires integration, compilation and merging of many disparate data types into a three-dimensional subsurface characterisation of important hydrogeological features (Bork and Rohdenburg 1986; Peck *et al.* 1988). The hydrogeological framework can then be used as input into sophisticated numerical groundwater flow models. The application of such models requires knowledge of model flow and transport parameters, boundary and initial conditions for each element. This dictates the need for three-dimensional Geographic Information System (3D GIS) (or 3D Geoscientific Information Systems – GSIS), for characterisation of hydrogeological features (*e.g.* Raper 1989; Faunt *et al.* 1993;

Fisher 1993). Most present 3D GIS are extensions of 2D GIS, adding the depth, *z*, dimension through multiple isometric bedded surfaces of the same *x*-*y*-co-ordinate system and resolution (Raper 1989). This quasi-3D approach cannot represent three dimensional surfaces like foldings and faults, but may be adequate for homogeneous aquifers and simpler stratigraphies. If data are in a rectangular grid square (raster) format each 3D cell is called a voxel (*i. e.* from **vo**lume pi**xel**). This data format is well suited as input to finite difference models. More advanced models such as discrete fracture network models (usually based on finite elements) must be based on more advanced 3D GIS models. The coupling between the GIS and the model can be either loose, the GIS output being used as model input after necessary transformation of formats, or intermediate, with the GIS data and model data sharing the same format. According to our knowledge no seamless or totally integrated system is yet available, but under development (*e.g.* Batelaan *et al.* 1996).

This article focuses on the initial phase of local groundwater flow characterisation, the development of a 3D hydrogeological framework model (AQUIFER). The model is tightly integrated with the GIS system IDRISI and loosely coupled to the 3D finite difference model MODFLOW (McDonald and Harbough 1988), or alternatively, the 2D finite difference flow and transport model MOC (Konikow and Bredehoft 1984). The ultimate objectives are to assess quantitatively the 3D distribution, direction and rate of movement of contaminants in the subsurface. The article describes the application of the framework model to a complex aquifer in South Eastern Sweden.

Materials and Methods

The hydrogeological analysis undertaken can be divided into four fundamental modules (*cf.* Turner 1989):

a) characterisation of surfaces and profiles, digitising
b) creation of a 3D GIS data base through expert knowledge inference
c) evaluation of the 3D data set and iterative improvement, sensitivity analyses
d) groundwater recharge, flow and contaminant transport modelling

This article descibes steps a)-c). Step d) has been briefly reported elsewhere (Knutsson and Kylefors 1995).

The study area is situated in South Eastern Sweden, near the town of Kalmar (Fig. 1). The esker aquifer studied is used for the water supply of Kalmar town (200 l/s), and is recharged with water from the nearby stream Hagyån (Hörberg and Kylefors 1986). The study was performed because of the construction of a new highway (Fig. 1). The esker has a very complex stratigraphy with highly varying depths. It is underlain by sandstone with low permeability.

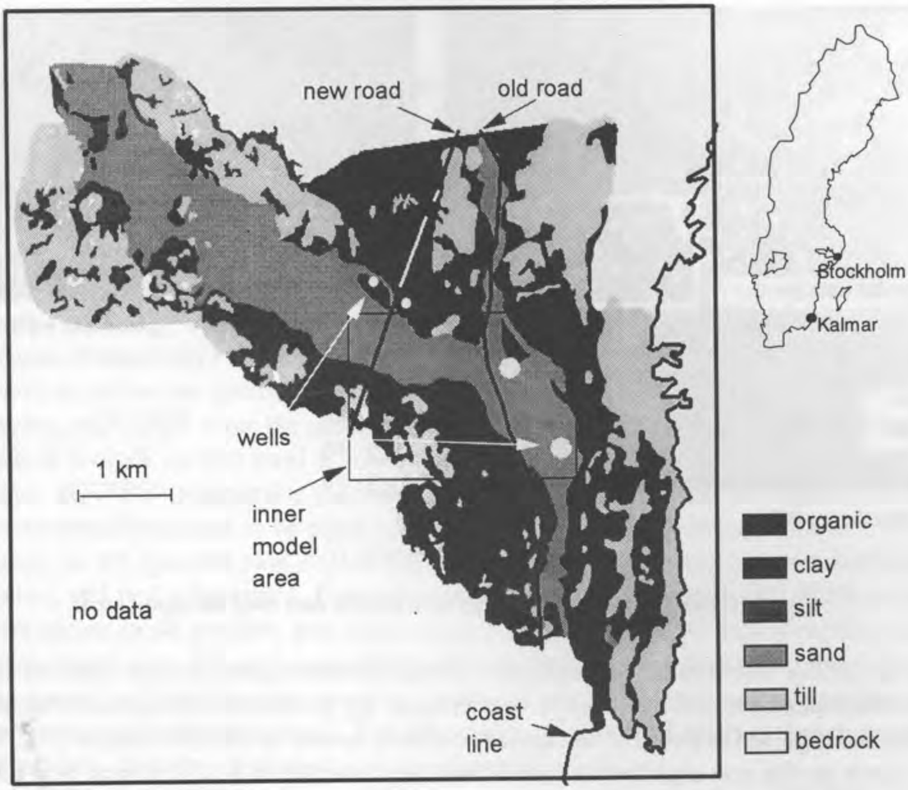

Fig. 1. Study area, with geological map over the Vassmolösa esker.

Geology was digitised based on a geological map (Knutsson 1966) (Fig. 1), and elevation data were taken from digitised contour lines (Fig. 2). These vector data were transformed to raster format, with resolutions of 25, 50, 100 and 200 metres. Interpolation of contour lines was done using linear interpolation of vertical, horizontal and diagonal profiles (Eastman 1993). The 200 metre resolution data was used for a larger area, and a smaller inner area was modelled with data of 50 metre resolution (Figs. 1 and 2).

Several profile data sources were available. The major data set was approximately 250 test bore holes made for hydrogeological investigations (Hörberg and Kylefors 1986; Knutsson and Kylefors 1995). Typically each profile contains information on soil stratigraphy, and depth to bedrock. Later profiles (28 points) also have information of boulder frequency, colour of return water from flushing, and water permeability. Apart from these data sets confined to the esker itself, profile data for production wells and private wells were available through the Swedish well archive at the Swedish Geological Survey and the local municipality and its consultant (Hörberg and Kylefors 1986). Two profiles of seismic data were also available (Aaltonen

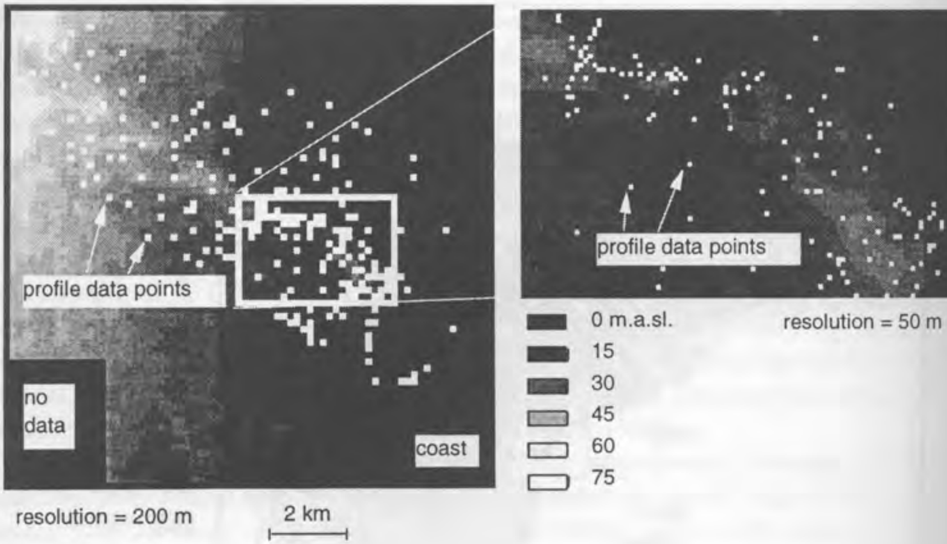

Fig. 2. Elevation model and points with profile data over the study area.

et al. 1995). These latter sources only contained information on the depth to the groundwater table and the depth to the bedrock. All profile data points were identified and digitised as points in the same coordinate system as the GIS images (Fig. 2).

Each profile was digitised and saved as a separate file in ASCII format (via EXCEL), given the same label as the corresponding digitised point. Points to be used for creating horizontal images are given in a file of IDRISI vector format. In this way the user can decide which points to include or exclude for creating the 3D database. Apart from profile data a digital elevation model (DEM) is needed. The 3D database will be created with the same horizontal resolution as this DEM, meaning that the user can decide output resolution. Vertical resolution is directly given by the user. By including a digital geological map, the user can infer knowledge to avoid logically incorrect values in the created database (*e.g.* dependent on stratigraphic inconsistencies).

Using the command line syntax of IDRISI4.1 a program (AQUIFER) was written (by TG) in PASCAL that extracts selected information from maps and profiles and creates horizontal images on the users request. The user can choose to create horizontal images based on absolute elevation, or slices with equal distance to the land surface or any other surface created by AQUIFER (*e.g.* groundwater table or bedrock surface). Interpolation is done either as distance weighted average, or weights equal to the reciprocal of the distance square, where, in the latter case, the number of points and the search radius must be defined by the user (see Eastman 1993). The further modelling will be carried out within a geostatistical framework, which will allow for error estimates of the interpolation (*e.g.* by Kriging). Moreover, the uncertainty in the result parameters will be studied by means of conditional simulation (see *e.g.* Journel and Huijbregts 1978).

All GIS operations are embedded in the model, and automatically called upon. After feeding information to the model, AQUIFER starts by creating images for bedrock surface and groundwater table. Secondly soil depth above the groundwater table and depth of the groundwater zone are calculated. This is done either as direct interpolated depth values, or as the difference between the pre-interpolated boundaries (*e.g.* soil depth = soil surface – groundwater table).

The main operation is then creation of multiple bedded surfaces of the available profile data (*e.g.* material composition, degree of sorting, boulder frequency, hydraulic conductivity). Output is either for the whole profile depth, or for the zone above or below the groundwater table. If depth to bedrock is registered to be unknown, AQUIFER takes the value from the created elevation model of bedrock surface. If bedrock surface level is above the bottom of the borehole (physically impossible) AQUIFER regenerates the bedrock surface elevation model setting bedrock at the mismatching point to be equal to the borehole bottom (or lower at the users request). In the opposite case AQUIFER registers unknown values between borehole bottom and bedrock surface. For each vertical slice to be created AQUIFER seeks information in all profiles, and restructures it as vector data. If data is missing the point is neglected. For each type of data the user decides if the horizontal image is to be created by Thiessen polygons or by interpolation. In the latter case the interpolation must also be parameterized. The generation of horizontal slices is then done automatically down to the deepest registered profile point.

AQUIFER is loosely connected to an expert system interface (GUIDE) for knowledge inference (Chmiel and Gumbricht 1996). GUIDE can be used for preprocessing of profile data, *e.g.* for producing an integrated value of hydrogeological importance based on other profile data. GUIDE can also be used for post-processing of generated layers. In this project GUIDE was used to exclude non-logical values of material composition and hydraulic conductivity based on knowledge of stratigraphy and the pre-existing geological image. That is regions with moraine as surface soil were changed to this soil type through the whole profile, and hydraulic conductivity in those areas were set after moraine values solely.

Results

The complexity of the Vassmolösa esker called for several iterations before a satisfactory hydrogeological framework was achieved. Some points with erroneous data were discovered and had to be omitted. The three map sources (*i.e.* geology, elevation and points with profile data) were all in different scale and quality, causing problems with positional accuracies. Fig. 3 shows a) groundwater table, b) bedrock surface, and c) the depth of the groundwater zone calculated as the difference

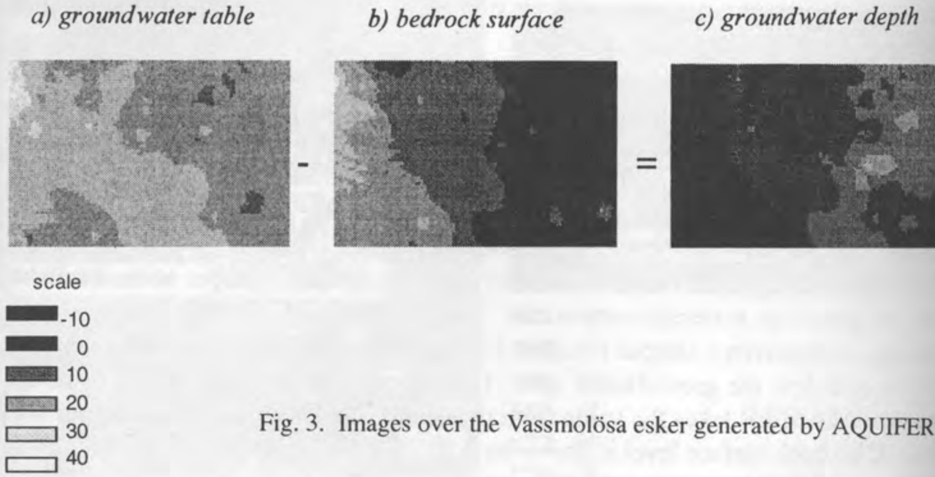

Fig. 3. Images over the Vassmolösa esker generated by AQUIFER.

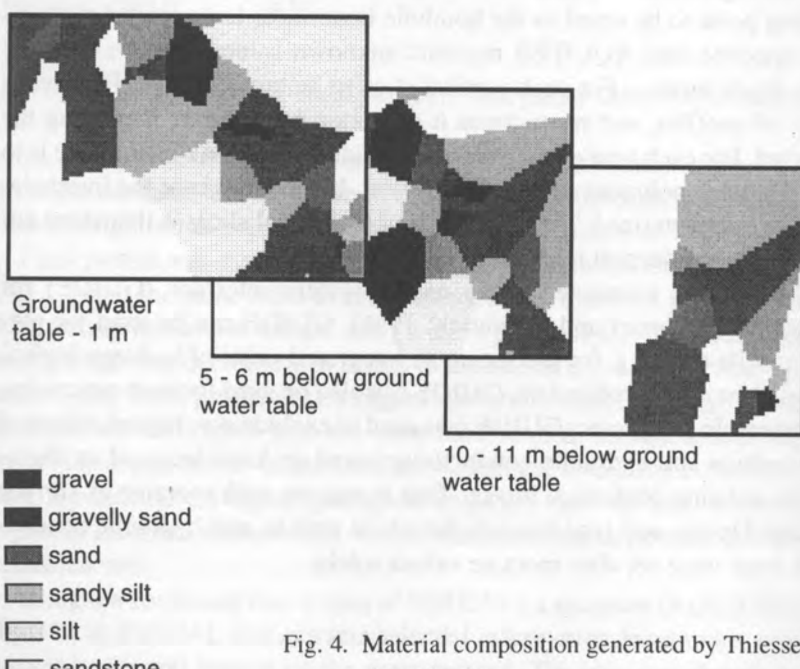

Fig. 4. Material composition generated by Thiessen polygons at three depths.

between a) and b). Fig. 4 shows material composition (interpolated via Thiessen polygons) for three sliced surfaces parallel with the groundwater table (as given in Fig. 3a).

Transmissivity for the whole groundwater zone was calculated by adding conductivity estimated from material composition of one metre thick slices (Fig. 5a). In the groundwater transport modelling the surrounding moraine was set as a no-flow

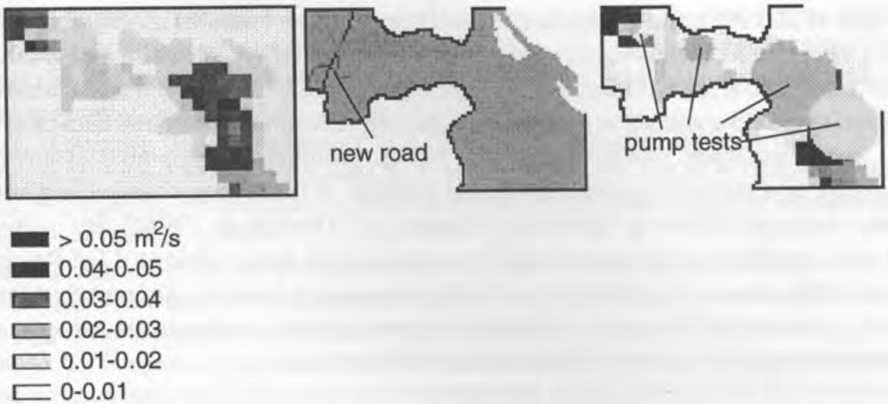

Fig. 5. Transmissivity model over the Vassmolösa esker and its surrouding, a) transmissivity below groundwater table, b) boundary conditions used in the modeling, and c) final transmissivity model used in the groundwater transport modelling.

boundary (Fig. 5b). Calibration was manual, based on forward driven changes in the data and parameterisations, seeking a best fit with transmissivity obtained from pump tests. The final transmissivity model was derived after several iterations, including adjustment of the groundwater table and draping information on transmissivity from four pump tests over the modelled ditto (Fig. 5c).

Discussion

The presented system was found to be a powerful tool for generating 3D datasets of different resolution based on 2D data. Different scenarios were comparatively easy to produce, once the profile and elevation databases had been built. However, the loose coupling requires some handicraft skill of the user. An intermediate connected system sharing the same data formats, or even a seamless integration, would facilitate the use of the model as a decision support system (*cf.* Furst *et al.* 1993).

The generated 3D dataset turned out to be sensitive to model parameterisation on *e.g.* interpolation technique and soil and groundwater depth calculations. Different groundwater tables can give different distributions of conductivity, especially when interpolation is done parallel with the groundwater table. A single error in the profile database can easily distort the whole model outcome. For instance by generating an underground bedrock (no-flow) dome. Positional errors due to the different map sources and their quality was a problem. This is illustrated in Fig. 1 by the mismatch between the old road and the esker (in reality the road is bound to the esker).

The high variability in hydrological features of the studied aquifer dictates the use of *e.g.* more sophisticated (3D) geostatistical methods or artificial neural networks

(Gupta *et al.* 1996), and the application of fuzzy logic and sensitivity evaluations (*cf.* Peck *et al.* 1988). A general trend is towards inclusion of visualisation and graphical user interfaces (*e.g.* Williams *et al.* 1996; Sokol 1996). Currently, the file handling related to the flow and solute transport modelling is facilitated with the help of a Visual Basic interface (Johansson *et al.* 1994). Another development is towards coupling to a surface hydrological model capable of modelling changes in groundwater recharge following land cover changes (*e.g.* Gumbricht 1996b). By inclusion of such capabilities, the system could be used as a risk assessment tool (*cf.* Reichard *et al.* 1990). Areas of application for such an integrated Decision Support System include groundwater pumping, risk of salt water intrusion, contaminant transport and risks of contamination from both point and diffuse sources.

Conclusion

The system should not be used unless in co-operation with local expertise, familiar with geological and/or hydrogeological conditions. However, the building of digital 3D hydrogeological framework models is not a trivial task. This calls for model transparency and good visualisation capabilities. For glaciated soils with small scale heterogeneity data sources of very good quality and positional accuracy are needed.

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