

# INTEGRATED 3D MODELLING OF SUBSURFACE GEOLOGY AND HYDROGEOLOGY FOR URBAN GROUNDWATER MANAGEMENT

## Digital geological 3D structure models provide capable and forward looking management tools.

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### ABSTRACT

Conceptual geological models of urban areas are an essential component of groundwater investigations as well as of urban groundwater management. For sustainable urban groundwater management there must be a coherent understanding of the local groundwater and aquifer system, which is unique at each location in respect of the particular groundwater setting and architecture. This paper presents two examples of 3D geomodelling in urban management using model concepts and requirements as well as interactive real time modelling results of subsurface geology. The application of integrative modelling concepts shows the concurrence with groundwater flow and transport models within a regionally contaminated urban aquifer system. The modelling results can also be exploited in GIS as well as in the 3D geological model to obtain detailed information concerning contaminated zones, exposure routes, and adsorption potential. Thus, the digital 3D structural models carry more importance than to serve only as a basis for groundwater modelling; they represent new forward-looking tools for integrated data management and decision support in urban groundwater management.

**Key words:** 3D modelling, geology, hydrogeology, water quality, urban management

## 1. INTRODUCTION

Urbanisation has a major impact on groundwater recharge in both quality and quantity as well as groundwater flow beneath cities. The impact is due to the import of large quantities of water as well as the extensive use of the ground for effluent discharge, waste disposal, and groundwater extraction. Hence, effective management of urban aquifers has to incorporate the negative effects on groundwater resources in the underlying groundwater systems. The effect on recharge arises both from modifications to the natural infiltration system and changes in natural drainage. These changes are induced by leakage from water mains and by wastewater seepage (Foster *et al.* 1993). The resulting effect on the quality of recharge is generally adverse, urbanisation processes being the main causes of severe, but essentially diffuse, pollution of groundwater and rising levels of salinity (Morris *et al.*, 1994; Morris *et al.*, 1997). Widespread groundwater contamination results from chlorinated hydrocarbons and other organic compounds. Additional adverse effects on a more localised basis are due to pathogenic agents in upper aquifer systems with insufficient sewage and waste-disposal infrastructure (Marsalek *et al.*, 2006). Changing groundwater-related issues that could affect urban buildings and infrastructure result from lowering of groundwater levels, by high extraction rates for water supply and by rising water-tables. The general change in water quality can create significant problems especially in the latter situation.

Morris *et al.* (1997) point out, that for a sustainable urban groundwater management, there must be a coherent understanding of the local groundwater/aquifer system, which is unique at each location in respect of its particular groundwater setting and aquifer architecture. Such implies an adequate knowledge of the subsurface geology that establishes the basis of the groundwater interaction influencing engineering, infrastructure, and related water resources problems. Aquifer vulnerability mapping, a specific need in most of the developing countries, is based on land use as well as on the upper groundwater conditions defined by the aquifer geology. Therefore, land use planning has to

follow robust matrices that indicate what activities are acceptable and what has to be done to increase awareness of the role and susceptibility of the subsurface to contamination.

In order to provide subsurface geological data for urban groundwater management, over the last 10 years digital 3D modelling of geological structures has markedly increased, moving from a 2D mapping to a 3D modelling culture related to advanced software and IT capabilities. Such is natural progression in data handling and in subsequently coupled modelling strategies and decision support in regional management.

Recent examples from Brussels and Vienna show that data preparation of subsurface information is, to some extent, done using Geo-Information-Systems, which allow only 2.5 D processing. Nevertheless, the increasing examples of 3D mapping and geological modelling of different cities in Europe, such as Glasgow by the BGS (UK) (Culshaw, 2005), Vienna (Pfleiderer and Hofmann, 2004), Magdeburg by the State Geological Survey of Saxony-Anhalt (Germany) (Neumann *et al.*, 2006), as well as the city of Halle (Saale) (Wycisk and Schlesier, 2006) shows the increasing applicability of this digital 3D modelling concept in practice.

Due to future needs involving consistent data management, developing countries such as Bangladesh are also implementing 3D geological mapping and modelling for the Greater Dhaka City area. The major objectives of this project are to provide subsurface information for hydrogeology and geotechnical applications as well as environmentally related planning issues using a flexible and dynamic model-based system (Asaduzzaman *et al.*, 2006). Objective and project defined results on demand indicate the progress of this approach rather than the static 2D analogue map printed solutions. This progress will be of future importance for most of the developing countries.

Depending on the available information and quality of data for urban water management, the coupling of urban drainage models with numerical groundwater simulations for integrated water management is becoming increasingly important (Schrage *et al.*, 2005, Morris *et al.*, 2007). This integration provides the needed basis for sustainable strategies using the 3D-generated subsurface digital information for integrated modelling and management. This paper describes examples of different and, to some extent, innovative applications from urban areas of Germany.

## 2. 3D GEOMODELLING IN URBAN MANAGEMENT

### 2.1 Model concepts and requirements

With advances in 3D modelling software and visualization tools over the last few years, as well as the increasing 2.5D and 3D GIS applications, digital subsurface information of local to regional scales has become more applicable and available (Culshaw, 2005, Wycisk *et al.*, 2002). This aspect is in line with the increasing needs of conceptual and structural geological models in the broad fields of urban groundwater flow and transport simulation, of geotechnical investigations, as well as for predictive results of geological subsurface information for infrastructure planning.

Due to the complexity of 3D modelling software tools and the specific situations of regional geology, users might be not aware of the differences in their models or resulting limitations and disadvantages. The availability of subsurface data in quality and quantity could limit the modelling approach. Apart from this general question, the regional setting and coverage of subsurface drilling information has to often bridge large information gaps. 3D modelling software and visualization tools are available using geostatistical algorithms (e.g. GoCAD, EVS/MVS, Rockworks) that working completely differently than the TIN-based (triangulated irregular net) interpretation using intersecting cross-sections (GSI3D). The shortcomings of automatic contouring by statistical and geostatistical algorithms are compensated by the use of constructive intersected cross-sections and mapping information.

The major obstacles in regional 3D modelling have been summarized by Berg and Keefer (2004) and can be confirmed by our experience from different regional models. Geological data verification is time-consuming, and many projects that require groundwater modelling investigations have not had sufficient time or money to obtain the detailed geologic interpretations needed. The interpretation of complex geological sequences, especially in the Quaternary, requires experience in regional stratigraphy and sedimentology. Without this specific regional knowledge, any 3D mapping and modelling will be either incomplete or will fail.

The expected results of visualisation and analysis of geological 3D models offer more advantages when compared to classic two dimensional analogue methods of urban groundwater management. The main aspects are:

- Visualisation and analysis of the subsurface to deliver a decision support system for urban planners, managers and decision makers;
- Integration of various methods of investigation (hydrogeology, hydrochemistry; geophysics, geotechnics, infrastructural planning)
- Attributing and coupling to groundwater and surface water models;
- Analysis prediction and visualization of subsurface information;
- Consistent GIS-based IT-infrastructure, consistency of the data base, adapted to monitoring and management systems.

## *2.2 Constructive cross-section net-based interpolation*

The use of constructive cross-section net-based interpolation approaches are of advantage when one has unbalanced regional coverage of drilling information in complex and heterogeneous lithological subsurface units. The modelling process with GSI3D is based on the creation of a series of intersecting user-defined cross-sections. The entire stacking order of all deposits in the study area has to be defined stratigraphically and sedimentologically, and a generalized vertical section has to be created. The lithostratigraphic classification of the sedimentary succession within a consistent regional stratigraphic framework is more helpful than a pure grain-size of lithology-based approach for groundwater modelling. Most of the software tools allow the input of 2D mapping or surface information, especially from areas with a less dense borehole record. GSI3D allows modelling of the distribution and geometry of sedimentary layers by knowledge-based control of the modeller, which is especially needed for heterogeneous aquifer systems and/or artificially formed lithological units within urban settlements. GSI3D is currently intended for use in the near-surface modelling of surficial and Quaternary sediments (Neber *et al.*, 2006). The software is used by the British Geological Survey on different mapping scales and in combination with GoCAD for deep subsurface investigations and geological modelling (Culshaw 2005), also for regional investigations of urban groundwater contaminated mega-sites (Wycisk *et al.*, 2002, Wycisk *et al.*, 2004, Wycisk *et al.*, 2005).

## *2.3 Statistically-based 3D interpolation*

Uneven and spotty distribution of geological drilling information is one of the major obstacles in regional subsurface modelling with automatically contoured distributions and thickness of layers in urban areas. In the case of known geology or sufficient coverage of drilling information, the statistically-based interpolation tools provide a less time-consuming modelling approach. As an example, EVS (Environmental Visualization System; C Tech Development Corp., Santa Barbara, Ca.) provides true 3D volumetric modelling together with 2D and 3D kriging algorithms with best fits of variograms to analyze and visualize geoscientific and environmental data. EVS/MVS allows the seamless integration with ArcView GIS, as well as with Modflow and MT3D. The 3D modelling of the subsurface geology with EVS is based exclusively on selected drilling information and the geostatistical interpolation of the individual layers. This procedure can lead to different results in cut-and-fill structures of Quaternary sedimentary channel fills, as well as any artificial structures e.g. subsurface dumps.

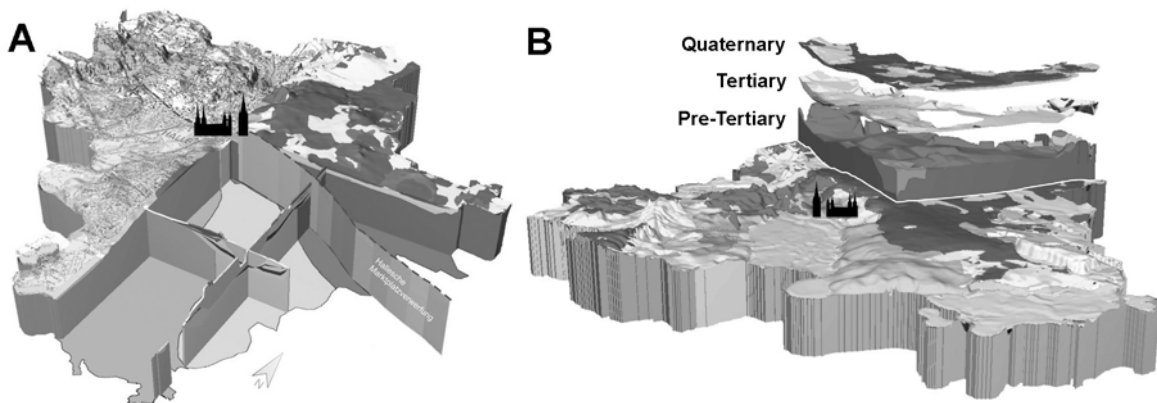
### 3. INTERACTIVE 3D-MODELLING OF THE SUBSURFACE GEOLOGY

In conjunction with the City of Halle (Saale), a digital 3D spatial model was constructed for the total city area of 135 km<sup>2</sup>. Consequently, Halle is one of the first cities in Germany to have available an extremely sharp and detailed 3D volume model of its geological subsurface, composed of 24 layers (Fig. 1A). The 3D spatial model provides the basis for a future GIS supported information and prognosis system. Such a system also provides the basic framework for future extensions to information and decision-making systems. The possible applications lie in the areas of geological and geotechnical recognition of particular locations of interest, of groundwater and environmental protection, as well as for environmental and city planning.

#### 3.1 Geodata and model construction

Innovative use of the 3D spatial geological model of Halle (Saale) City is based on the extremely precise modelling of the geological subsurface. At the same time the ordering and juxtaposition of the geological layers in the domain provides information on the most important groundwater aquifers and aquitards. The heterogeneity of aquifers and aquitards is very high and is due to the structural geological setting. The urban hydrogeology is characterized by different porous aquifers with frequent local aquifer/aquifer contact areas as well as by fractured aquifers of different lithologies (Fig. 1B).

The basic data for the model are obtained from a network of 32 cross-sections based on drilling information. The precision of the horizontal resolution of the spatial model is 40 m x 40 m, while the vertical resolution is on the order of cm depending on available core data.



**Fig. 1:** Geological model of Halle / Saale. Fig. 1A shows virtual cross-sections and the main faults striking through the city. In Fig. 1B the distribution of 24 individual layers, e.g. aquifers and aquitards, is visualized to give insight to potential aquifer connections and layers with high adsorption capacities.

Completely new interpretation and evaluation possibilities arise from the superposition of information at different depths in the subsurface in the form of spatial views of individual layers, “virtual” cross-sections, as well as hydrogeological analyses with “real” views from aerial photographs or maps.

In the future this “augmented reality” will allow one to obtain a new level of quality in the geosciences and environmental disciplines. Such can be presented in the forms of maps or interactive digital 3D visualizations, and can be used for specific technical questions in real time.

The possible uses of an interactive device, such as a subsurface Viewer, enable the direct investigation of geological and hydrogeological information. The results can be presented as virtual boreholes, as vertical and horizontal sections, as thematic maps, as well as locating 3D bodies contained in the modelled area with sharper spatial precision. The spatial model was constructed with

GSI3D, and the subsequent transition to the Subsurface Viewer was undertaken in cooperation with Lithosphere Ltd. & Co KG, Cologne.

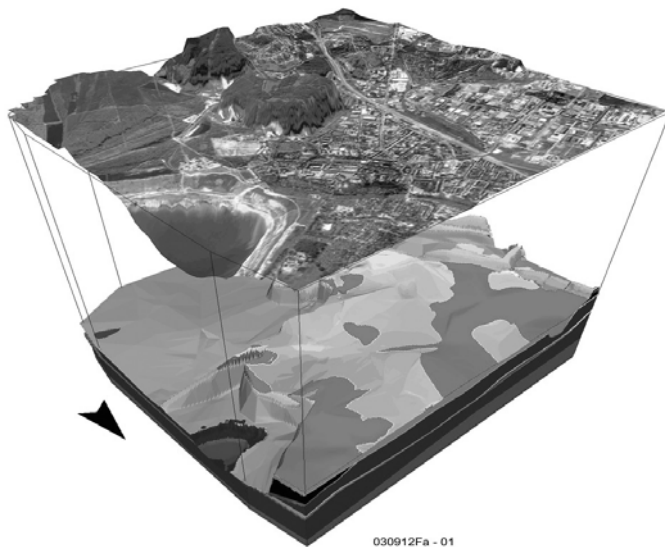
### 3.2 Interactive modelling in real time

The advantage of the modelled system allows interactive modelling in real time using an independent viewer system. This Subsurface Viewer is based on the independent model construction by modellers and also on the application with the Viewer System by users, who do not need specific modelling knowledge. The separation of the modelling system into an active part, which includes modelling and subsequent improvement by implementing new drilling information, and a user oriented part, allowing only the analytical and predictive features of interpretation, ensures the integrity and quality of the primary 3D modelling database. The software-tool is linked to each respective model, enabling users to investigate the 3D setting of the geological subsurface immediately in an easy to understand format. The colour coding of each modelled geological unit is defined according to analogue standards of geological maps. In addition, it is possible to visualize the model colour scheme according to specific applied geological parameters such as hydraulic conductivity, geotechnical values, etc.

## 4. INTEGRATIVE MODELLING CONCEPTS OF CONTAMINATED URBAN AQUIFERS

### 4.1 Environmental setting of the former industrial mega-site

Large scale groundwater contamination sites such as the urban area of Bitterfeld-Wolfen in Germany, are characterized by different environmental impacts caused by the former chemical industry and extensive landscape devastation by lignite mining over the last 100 years or more. Due to the multi-source regional contamination in the upper and lower aquifers, an integrated assessment is needed of the groundwater quality and of the local risk areas. Therefore, a regional 3D spatial model of distinct individual environmentally related core modules has been developed for the urban Bitterfeld - Wolfen area. Two investigation projects (SAFIRA I and II) have assessed the long term development for the urban and industrial areas in terms of a risk-based land management approach (Fig. 2).



**Fig. 2:** Former and future land use are an important factor for contaminated upper urban aquifers. Geological structures defining aquifer/aquifer contacts, as shown here for the Bitterfeld area, are influenced by abandoned mining and infrastructure projects. Both aspects give a completely new view to management strategies.

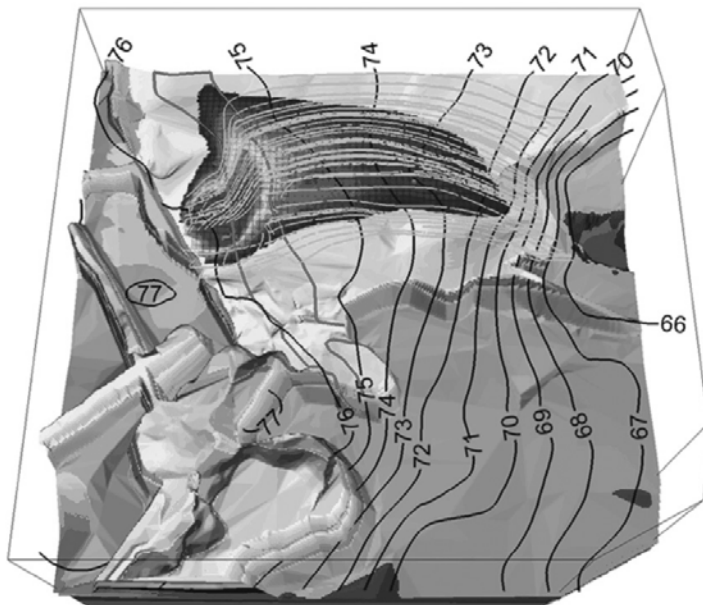
Due to the large affected urban area and rural vicinity of more than 60 km<sup>2</sup>, an intensive groundwater monitoring program has been operative for more than 15 years. More than 170 individual organic substances, as well as 30 inorganic substances, have been monitored. The importance of the

former industrial area is characterized by the more than 40000 chemical plant workers during GDR time, by 15 industrial toxic land-fills, and by more than 5000 individual chemical substances during the nearly 80 years of industrial production in an urbane environment.

The most frequent substances are Tetrachloroethene (PCE), Trichloroethane (TCE), cis-1,2 Dichloroethane (cis-1,2DCE), Vinylchloride (VC), 1,4-Dichlorobenzene (1,4 DCB), 1,2-Dichlorobenzene (1,2 DCB), Monochlorobenzene (MCB), and Benzene. The regional distribution of contaminants and reflects their different and multiple sources and pathway relations. The cities of Bitterfeld and Wolfen, as well as several villages and the rural landscape of the alluvial plain of the high flood affected River Mulde, describe the environmental sensitivity to humanity and natural resources (Heidrich *et al.*, 2004, Wycisk *et al.*, 2003).

#### 4.2 GIS-based multi-source data management

To assess the complex environmental situation of the Bitterfeld-Wolfen area, a GIS-based spatial model was required that includes the heterogeneous aquifer setting in 3D and in as much detail as possible (Fig. 3). The subsurface information had to be available for a GIS-based assessment and predictive calculations correlated to surface information of potential receptors.



**Fig. 3:** Groundwater flow system in a complex geological structure in the case of the Bitterfeld area. The groundwater contours don not help in construction of the pathways. Only groundwater flow and transport models (based on detailed geological models) yield numerically appropriate results that can be used for the assessment of contaminant spreading.

Therefore, the following major information modules have to be integrated into the spatial model on a local scale, including the specific objectives and used modeling tools:

- Land-use classification;
- Groundwater contaminants;
- Hydrogeological data;
- 3D model of the subsurface geology.

The GIS data management for all hydrogeological and hydrochemical data was done with ArcView 3.x and ArcView 8.x (ESRI). The spatial model includes point data such as borehole data (lithology/stratigraphy), hydrochemistry, contaminants monitoring data, etc. (Wycisk *et al.*, 2007). The geological cross-sections, with their vertical 2D structure, were held in a special device for geological 3D models. The geological structures had to be held in a GIS database to obtain an interface to numerical groundwater modeling tools such as Feflow or Modflow. These data are stored in GRID of point formats in ArcView.

### 4.3 Integrated modelling of urban aquifers

To support the integrated modelling concept the high-resolution 3D structural model of the entire area was enlarged to about 65 km<sup>2</sup> (Wycisk *et al.*, 2005). This model allows volumetric calculations of partial or distinct sedimentary units, such as lignite-bearing strata, that are relevant for assessing the natural absorption potential and retardation processes inside the aquifer. The digital data set of the true 3D structural geology was used with reference to the hydraulic characterization for subsequent flow and transport models. The numerical groundwater model was carried out with two objectives:

1. Description of the hydrodynamic system and the pathway prediction assessing the exposure route of local contaminants as well as for optimizing the well observation sites;
2. Predictive calculations of the changed hydraulic situation after the once in a Century flooding of the Goitzsche mining lake and raised groundwater level in August 2002.

The numerical model consists of two parts: A groundwater flow model and a transport model based on the flow model. The modeling systems Modflow, ModPath and MT3D with the Visual Modflow 3.0 preprocessors and postprocessors were used for the studied areas. Figure 3 shows the integration of simulated results from high-resolution 3D geology as well as from flow and transport modelling. The resulting impacts of laterally changing hydraulic conductivity inside the aquifers by channel-fill structures or anthropogenic activities by humans are clearly shown and are underestimated in most hydrological models.

## 5. CONCLUSIONS

To generate an almost realistic scenario of urban areas, it is necessary not only to gather high-resolution land-use information, but also to have a model of the aquifer systems corresponding to the real world scenario of the geological subsurface setting. The “true” regionalization of hydraulic and contamination data is also needed. This statement is valid for most Quaternary sediments underlying urban areas representing heterogeneous aquifer conditions, especially from fluvial and deltaic environments. The 3D geological model also serves as a future consistent data base and for the prediction of modelling provide groundwater and engineering related deliverables for urban management. The new approach of digital 3D geo-data management also enables municipalities of developing countries to produce a capable upgrading system and forward looking management tool.

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