

3D Geological and Hydrogeological Modelling – Integrated Approaches in Urban Groundwater Management

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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. The resultant effect on the quality of recharge is generally adverse with urbanisation processes being the main causes of severe, but essentially diffuse pollution of groundwater and rising levels of salinity. 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. Changing groundwater related issues could affect urban buildings and infrastructure resulting from lowering of groundwater levels by high extraction rates for water supply as well as 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. It implies an adequate knowledge of the subsurface

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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. There 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) show 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. 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.

3D Geomodelling in Urban Management

Model Concepts and Requirements

With advances in 3D modelling software and visualisation 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 visualisation tools are available using geostatistical algorithms (e.g. GoCAD, EVS/MVS, Rockworks) that are 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 visualisation of subsurface information; and
- Consistent GIS-based IT-infrastructure, consistency of the data base, adapted to monitoring and management systems.

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 or 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., 2005).

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 analyse and visualise 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.

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 km². 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

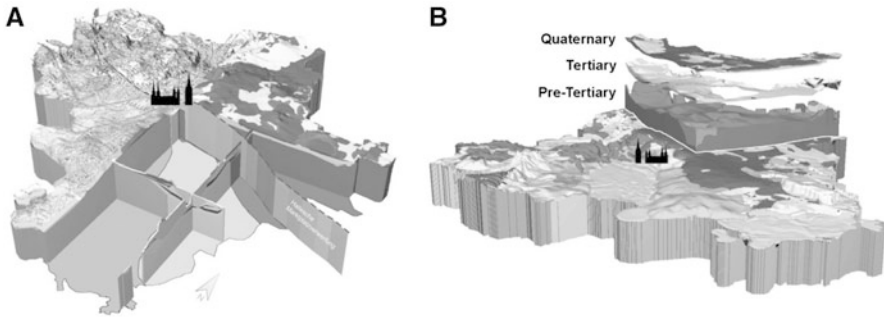


Fig. 1 Geological model of Halle/Saale. Fig. 1A shows virtual cross-sections and the main faults striking through the city. In Fig. 1B the distribution of 24 individual layers, e.g. aquifers and aquitards, is visualised to give insight to potential aquifer connections and layers with high adsorption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

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.

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 $40\text{ m} \times 40\text{ m}$, while the vertical resolution is of the order of cm depending on available core data.

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. This can be presented in

the forms of maps or interactive digital 3D visualisations, 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.

Interactive Modelling in Real Time

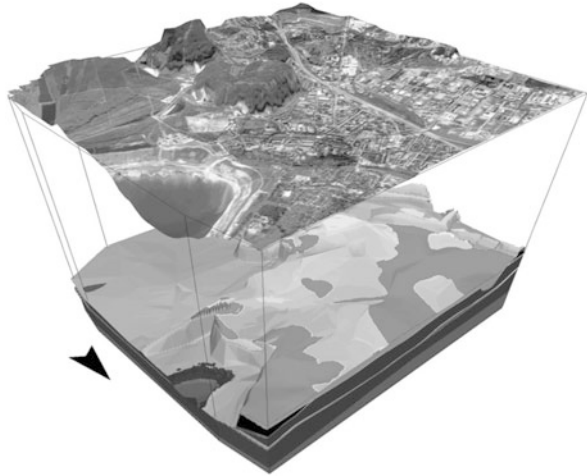
The advantage of the modelled system allows interactive modelling in real time using an independent viewer system. This subsurface viewer is based on the independent model construction by modellers and also on the application with the viewer system by users, who do not need specific modelling knowledge. 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.

Integrative Modelling Concepts of Contaminated Urban Aquifers

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 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



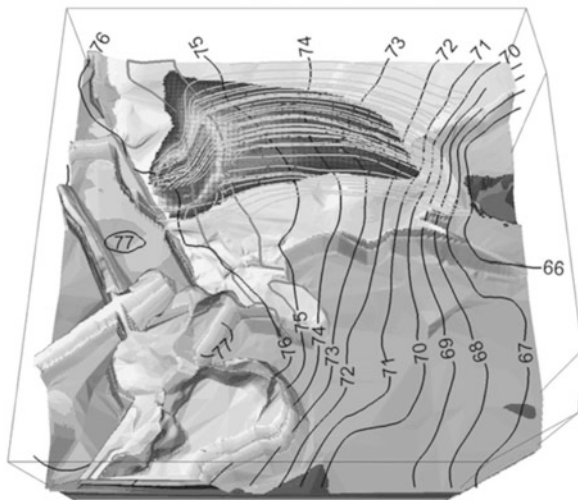
Due to the large affected urban area and rural vicinity of more than 60 km², an intensive groundwater monitoring programme has been operative for more than 15 years. More than 170 individual organic substances, as well as 30 inorganic substances, have been monitored. The importance of the former industrial area is characterised by more than 40,000 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 urban environment.

The most frequent substances are Tetrachloroethene (PCE), Tri-chloroethane (TCE), cis-1,2 Dichloroethane (cis-1,2 DCE), Vinylchloride (VC), 1,4-Dichlorobenzene (1,4 DCB), 1,2-Dichlorobenzene (1,2 DCB), Monochlorobenzene (MCB), and Benzene. The regional distribution of contaminants 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).

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 do 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 modelling tools:

- Land-use classification;
- Groundwater contaminants;
- Hydrogeological data; and
- 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 modelling tools such as Feflow or Modflow. These data are stored in GRID of point formats in ArcView.

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 km² (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; and
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 modelling 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.

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 provides 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.

References

- Berg, R.C. and Keefer, D.A. (2004). Three-dimensional Geologic Modeling: Challenging our Terminology and Understanding of Geological Maps. *In: Berg, R.C., Russell, H. and Thorleifson, L.H. (Eds.). Three-dimensional Geological Mapping for Groundwater Applications – Open File Series 2004–8.*
- Culshaw, M.G. (2005). From concept towards reality; developing the attributed 3D geological model of the shallow subsurface. *Quart. J. of Engineering Geology and Hydrogeology*, **38**:231–284.

- Heidrich, S., Schirmer, M., Weiss, H., Wycisk, P., Großmann, J. and Kaschl, A. (2004). Regionally contaminated aquifers – toxicological relevance and remediation options (Bitterfeld Case Study). *Toxicology*, **205(3)**: 143–155.
- Neumann, D., Schönberg, G. and Strobel, G. (2006). 3D-modeling of ground conditions for the engineering geology map of the city of Magdeburg. *In*: Culshaw, M., Reeves, H., Spink, T. and Jefferson, I. (Eds.). IAEG 2006 Engineering Geology for Tomorrow's Cities, The 10th IAEG International Congress, Nottingham, United Kingdom, 6–10 September 2006.
- Pfleiderer, S. and Hofmann, T. (2004). 3D-Visualisation of Vienna's subsurface. *In*: Schrenk, M. (Ed.) *9. internationales Symposium zur Rolle der Informationstechnologie in der Stadt- und Regionalplanung sowie zu den Wechselwirkungen zwischen realem und virtuellem Raum*, Proceedings of the CORP2004 and GeoMultimedia04, Vienna.
- Schrage, C., Wolf, L., Klinger, J. and Hötzl, H. (2005). Coupling Urban Drainage Models with Numerical Groundwater Simulations for Integrated Water Management. *In*: Sánchez-Vila, X., Cabrera, M.C. and Valverde, M. (Eds.). Proceedings of the IAH Workshop "From data gathering and groundwater modeling to integrated management", 4–8.10.2005, Alicante, Spain.
- Wycisk, P., Stollberg, R., Neumann, Chr., Gossel, W., Weiss, H. and Weber, R. (2012). Integrated methodology for assessing the HCH groundwater pollution at the multi-source contaminated mega-site Bitterfeld/Wolfen-ESPR (online first).
- Wycisk, P., Hubert, T., Gossel, W. and Neumann, Ch. (2009). High-resolution 3D spatial modelling of complex geological structures for an environmental risk assessment of abundant mining and industrial mega sites. *In*: *Computers & Geosciences*. Elsevier, Bd. 35.2009, 1.
- Wycisk, P., Weiss, H., Kaschl, A., Heidrich, S. and Sommerwerk, K. (2003). Groundwater pollution and remediation options for multi-source contaminated aquifers (Bitterfeld/Wolfen, Germany). *Toxicology Letters*, **140–141**: 343–351.
- Wycisk, P., Fabritius, H., Ruske, R. and Weiß, H. (2002). Das digitale geologische Strukturmodell Bitterfeld als neuer Baustein in der Sanierungsforschung. *Grundwasser*, **7(3)**: 165–171.