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Hamburg

TU1206 COST Sub-Urban WG1 Report

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Sub-Urba	an

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1 Introduction

Article 1 of the Water Framework Directive (WFD) lists as one of its purposes a contribution to "the provision of the sufficient supply of good quality surface water and groundwater as needed for sustainable, balanced and equitable water use ", as well as "a significant reduction in pollution of groundwater ...". Thus, in the light of the Directive, mapping of groundwater bodies as well as the assessment of water quality is crucial for the drinking-water supply in the City of Hamburg.

This case study wants to provide a picture of geological, hydrogeological and modelling data in Hamburg and the established workflow between BSU Geological Survey, BSU Water Management department and Hamburg Water, the state-owned public water supply company of Hamburg.

2 Urban geology data

BSU Hamburg receives borehole data from official (BSU-contracted) boreholes, private boreholes (e.g. ground source heat boreholes, private water supply boreholes) and site investigation work associated with urban regeneration and development. It is a legal requirement that borehole data is submitted to BSU Hamburg for any new borehole drilled, and that standardized lithological and borehole coding is used by contractors and drillers.

A BSU 'Data line index number' is assigned to borehole data once it is deposited to the BSU Geological Survey. The data submitted is then validated. Key data required for the borehole data to be useable are checked within the validation. Inconsistencies in the borehole data are manually corrected by BSU. The high cost associated with the validation of borehole data to BSU is deemed to be cost-effective in the long-term to have accurate and standardized borehole data. The lack of requirement to submit lithological borehole samples from private boreholes means the borehole log descriptions cannot be validated by BSU.

Once validated, borehole data are assigned a BSU Hamburg borehole ID number, and the data are stored within the BSU Geological Survey Oracle borehole database. Private and official borehole records are differentiated within the database by flags – "P" for private, or "S" for official. The Borehole Data Line is then completed, and the new data within the Oracle database becomes instantly available within other live-linked data portals internally within the BSU Geological Survey, and externally via the BSU and internet website (http://www.hamburg.de/bohrdaten-geologie) (Figure 1).

The level of validation performed by BSU Hamburg within the Data Line is unique in Germany – validation of borehole log lithological descriptions to borehole samples is only possible in BSU Hamburg due to the relatively small land area under the remit of BSU. In larger federal states, such as Bavaria which covers a large area across southern Germany, this level of validation is not practical.



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Figure 1 – Borehole data on the internet site "Bohrdatenportal" (BSU Geological Survey).

Applications of urban geological data:

- 1. Geological information for the building sector, well drilling sector and for geothermal projects.
- 2. Geological and hydrogeological map for different themes.
- 3. Geological and hydrogeological cross sections.
- 4. Database for the 3D geological structure model.

3 Urban groundwater monitoring

Due to complete reliance on groundwater for public water supply it is necessary for Hamburg to implement extensive urban groundwater monitoring to ensure groundwater resources are protected. However, it was recognized several years ago that the network was unnecessarily large, not all sites were yielding valuable data, the network was not targeted and therefore it was too expensive to maintain. In addition to the main monitoring network there are also monitoring networks maintained by Hamburg Water and the Hamburg Port Authority. Without a complete overview of the monitoring stations in the context of the urban groundwater system there was concern that key monitoring stations could be lost and a more coordinated approach was needed. As a result, BSU's geological survey and water department worked together to rationalize the network reducing it from >4000 <u>potential</u> boreholes down to 646 monitoring stations to monitor the groundwater level in different existing aquifers (Figure 2). Of these 646 stations there is a selection of 108 respectively 67 stations to analyze annually the chemical groundwater status of the shallow as well as deep aquifers.



Figure 2 – The 646 groundwater level monitoring sites (BSU Geological Survey).

3.1 Different parts of the monitoring network

Prior to rationalizing the monitoring network the boreholes were classified based on the hydro-stratigraphic unit being monitored – this being derived from the borehole geology and borehole completion information.

<u>Shallow Aquifer:</u> The rationalization exercise focused on the shallow Quaternary deposits for which there were the largest number of monitoring stations, reducing the network from 1054 boreholes to 539 monitoring stations. The Quaternary aquifer is perceived to be a higher priority for monitoring as it is susceptible to deteriorating water quality as a result of contamination from surface activities. It is subject to more subsurface disturbance through urban development and as an aquifer it is more heterogeneous.

<u>Deeper Aquifers</u>: The Tertiary aquifer is more homogeneous and is better protected from potential polluting activities by the overlying Quaternary cover requiring less groundwater monitoring. The Tertiary aquifer was not subject to the rationalization exercise with the existing 109 monitoring stations of high quality and required to understand the groundwater regime.

<u>Groundwater quality / WFD:</u> A sub-set of 157 boreholes from the Quaternary and Tertiary aquifers are used for groundwater quality monitoring, some of which are also groundwater level monitoring sites. Of these, 44 boreholes have been used for the purpose of the WFD reporting with particular focus on 1) areas of groundwater inflow to Hamburg, 2) areas

susceptible to saline intrusion, 3) the area around the salt dome which lies beneath Hamburg, and 4) areas where the groundwater levels are not affected by public water supply abstraction.

3.2 Monitoring Frequency

Prior to the rationalization exercise monitoring boreholes in Hamburg were dipped manually twice a month. This monitoring protocol was deemed to be labor-intensive and not cost-effective. Nowadays most sites have data-loggers installed which are readout every 2 months including sites that are tidally influenced. Sites that are prone to rising groundwater levels and groundwater flooding are telemetered and have associated trigger levels to initiate remediation.

3.3 Responsibility for the network and monitoring data

Whilst the geological agency and the water department worked collaboratively to rationalize the monitoring network and the geological agency provides on-going geological expertise, the water department is overally responsible for the network and is in charge of:

- Ensuring the monitoring is carried out this is completed by a third-party under a sub-contract. The cost of carrying out the groundwater level monitoring, including carrying out manual dips and downloading of data loggers, is estimated to be €40/yr/per site.
- Maintaining the sites.
- Reviewing each groundwater level site every 10 years and each water quality site every 5 years, including CCTV inspection, pump test and geophysical logs.
- Ensuring that all data from the main monitoring network and ancillary networks (e.g., Hamburg Water and the Port Authority networks) are entered into a corporate database.

BSU Hamburg (geological agency and the water department) are also committed to on-going review of the network to ensure that new boreholes are incorporated in the network in areas where there are current gaps and where old boreholes are decommissioned.

3.4 Generation of groundwater contours

One of the primary uses of the monitoring network data was to generate groundwater contours for the shallow Quaternary aquifer (Figure 3). There are insufficient monitoring points in the deeper Quaternary aquifers to generate contours. The work was carried out by the geological agency and the water department and required a significant investment of time given the complexities of the shallow hydrogeological system, such as the tidally influenced areas, harbor area and flood management zones. The contours were generated in ArcGIS using the interpolation packages with different interpolation methods applied to

different aquifer settings. Spurious data points were manually corrected and helper markers were inserted to adjust contours where the modelled interpolation was insufficient. Surface water elevations were also used where there was a known groundwater-surface water interaction. Maximum, minimum and middle groundwater level contours have been generated in addition to contour maps for key specific time periods (max. 2008, min. 1996, and middle 2010). The groundwater level contours are freely available online (http://www.geoportal-hamburg.de/Geoportal/geo-online/).



Figure 3 – Groundwater contour map of Hamburg (BSU water department).

Based on this contour map and in consideration of the elevation model a map of the depth to water table has been developed (Figure 4).



Figure 4 – Map of the depth to water table in Hamburg (BSU water department).

The long-time measurement of the water table allows analyses of the groundwater level development in the past (Figure 5).



Figure 5 – Groundwater level trend 1982-2012 in Hamburg (BSU water department).

Hamburg has successfully targeted the monitoring network to specific drivers (e.g., saline intrusion, rising groundwater levels) and has a good appreciation of where in the city particular groundwater issues do occur.

Applications of urban groundwater monitoring data:

- 1. Generation of groundwater contours for the Quaternary and Tertiary aquifer.
- 2. Description of depth to water table for the shallow Quaternary aquifer.
- 3. Description of the groundwater level development particularly in the areas with rising groundwater levels.
- 4. Data base for rainwater infiltration maps and potential evaporation maps.
- 5. Description of the groundwater quality for the Quaternary and Tertiary aquifer.
- 6. Monitoring or detection of saline intrusion.

4 Groundwater monitoring and modelling of the urban groundwater system of Hamburg

4.1 Hydro-stratigraphical Modelling

In conjunction with the other state geological agencies in Northern Germany, the geological units have been classified into a standard hydro-stratigraphy. The application of the hydro-stratigraphic codes is aided by the large number of borehole records for the city and the use of both stratigraphical and lithological borehole coding. The hydro-stratigraphy is based on the geological sub-division units which have been amalgamated or subdivided based on their hydrogeological properties.

The knowledge of the structure of the substrate is the basis of hydrogeological mapping. It is a rough distinction between aquifers and aquicludes. These hydrogeological units are characterized by a hydro-stratigraphy letter-number combination where "L" stands for aquifers and "H" for aquicludes (Manhenke et al. 2001). The unit numbering is labeled by counting from the youngest to the oldest; subsequently Holocene river sands are labeled L1, the Saalian glaciation is given the term H3, and the Lower Lignite Sands the name L6 (Figure 6).



Figure 6 - hydrogeological units of aquifers and aquicludes in Hamburg (BSU Geological Survey)

The hydro-stratigraphical classification has been used to assign the boreholes of the groundwater monitoring network to the correct aquifer unit and has improved the groundwater modelling.

Applications of hydro-stratigraphical modelling:

- 1. Description of the hydrogeological units and the groundwater bodies.
- 2. Allocation of groundwater monitoring wells to the hydrogeological bodies.

4.2 3D Geological Modelling

A 3D geological model of Hamburg is currently being developed by the geological agency. The model is being developed in GOCAD and incorporates the Tertiary deposits, the base of Quaternary and the infill of the buried valleys (Figure 7). There is an intention to extend the model to the overlying Quaternary deposits, but the heterogeneous nature of these deposits (e.g. lenses) is difficult to capture. The model primarily uses the coded borehole records to extrapolate 3D volumes of the geological units. The aim of the 3D geological model was to show the geological structure of the Hamburg area and to validate, control and integrate all available data produced by different geological and geophysical methods over a long time with different quality standards (Figure 8).



Figure 7 - 3D geological model of Hamburg (BSU Geological Survey)

In the first step of the project all available data were used to set up a so called 3D starting model. In the second step, the geophysical data was integrated into the starting model and these were used to optimize it. The quality of the available data in the first step was quite different. Therefore, all information not relevant for the modelling, was eliminated and inaccurate descriptions were reinterpreted if possible. An optimized set of borehole data was used for the modelling. The attempt to model the buried valleys and the salt domes by

using only the borehole information did not match the geological structure. In order to get a better result, more data was incorporated, especially maps and cross-sections containing geological interpretation. By using the additional structural information the valley structure could be produced by the GOCAD program.



Figure 8 – All available data from maps, cross-sections, seismic lines and drillings (BSU Geological Survey)

The cross-sections are not used directly in the GOCAD calculation, but are imported after preprocessing into the GOCAD project to cross-check the model outputs with the cross-sections (Figure 9). The significant number of interpreted cross-sections and the publicly-funded coded boreholes are freely available online (<u>http://www.hamburg.de/bohrdaten-geologie</u>).



Figure 9 – GOCAD project to cross-check the model outputs with the cross-sections (BSU Geological Survey)

The 3D geological model has been used as input data for the groundwater model. Furthermore, models of temperature and salinity are built up and integrated into the 3D geological model.

Applications of 3D geological modelling:

- 1. Establishment of a non-contradictory geological interpretation of the subsurface
- 2. Verification of new borehole data
- 3. Basis for a temperature and salinity model for Hamburg
- 4. GOCAD provides the data basis for the 3D printer for creation of block models
- 5. The 3D geological model can be used as input data for the groundwater model

4.3 Groundwater Modelling

Coherency across the groundwater monitoring network with regards to hydro-stratigraphy and the geological stratigraphy has facilitated the development of a unified groundwater model for Hamburg. Originally there were three regional groundwater models and further smaller-scale models covering Hamburg, each developed by different organizations using different software. There were significant differences in the aquifer designations, properties and boundary conditions across the regional models making a consistent city-wide assessment of groundwater issues impossible. There was significant incentive to create a unified groundwater model for the region of Hamburg to ensure the protection of groundwater resources, specifically:

- Develop regional water-balances and assess regional groundwater flow.
- Assess hydraulic conductivity between shallow Quaternary and deeper Tertiary aquifers.
- Assess the impact of new licensed supplies in the context of the regional groundwater system and collection of more information about the influence of existing catchment areas is needed.
- The increased use of the deeper underground warrant the development of source protection zones for the public water supplies from the Tertiary aquifer.
- Optimize groundwater and surface water measurement programs by using the results from the groundwater model
- Concepts for groundwater abstraction in catchment areas with variable salt-/fresh water boundary.

The groundwater model comprises 16 layers covering the Quaternary and Tertiary units and has been developed using SPRING, a finite-element modelling code. SPRING was used in preference to MODFLOW or FEFLOW as its grid structure is more suited to deal with irregular geological formations such as salt domes, buried valleys and lenses where the tapering of layers require a section of zero thickness (Figure 10).



Figure 10: mapping of salt domes and buried valleys due to SPRING layer concept of zero thickness (cross section from the regional groundwater model Hamburg), (Consulaqua, Hamburg Water)

Another benefit of the SPRING software is to allow model segments to be extracted from the regional model complete with model properties and boundary conditions, refined (e.g. grid refinement, addition of layers) and reinserted to the regional model (Figure 11). In this way

detailed problems can be processed within short calculation times and information from the detailed modelling can be re-imported into the regional model. Especially for a large-scale model like the Hamburg groundwater model with about 4.500 km² this workflow represents a great advantage.



Figure 11: Cut and reinsertion of model sections

The model code also allows flexibility with respect to layer thicknesses as they can be adjusted easily as part of the model calibration process.

STRING, a complementary software to SPRING, can be used to display an intuitive animation of the groundwater flow either in horizontal or in vertical cuts through the model area. STRING uses the calculated groundwater flow data derived in the SPRING simulations. With this approach, it is possible to visualize, interpret and understand highly complex flow regimes, and e.g. catchment zones for the public water supply can be defined (Figure 12).



Figure 12: picture from STRING animation, horizontal cut from groundwater model Hamburg, Curslack and Billbrook well fields (Consulaqua, Hamburg Water)

Geological surfaces of the Tertiary geological units were defined using the 3D geological model and imported directly into the groundwater model (Figure 13). The Quaternary geology which has not been modelled in 3D yet, was simplified down to three geological units for the groundwater model. Additional layers were included within the groundwater model to capture the geological complexity of the buried valley systems.



Figure 13: 3D-groundwater model Hamburg, (Consulaqua, Hamburg Water)

The groundwater model has been calibrated using the data from the monitoring network. First a steady state calibration has been conducted for the year 2010 which represents mean groundwater conditions. Figure 14 shows an extract from the groundwater model Hamburg in which isopotential lines of the lower tertiary aquifer are shown. Differences between measured and calculated hydraulic heads are shown in magenta or blue circles. The extension of the buried valley is shown in grey colour.



Figure 14: Isopotential lines for the lower tertiary aquifer, differences between measured and calculated hydraulic heads (Consulaqua, Hamburg Water).

In addition to the steady state calibration a transient calibration has been conducted using about two hundred measured hydrographs from groundwater monitoring wells over a time period from 2005 until the end of 2011. Figure 15 shows an extract from the groundwater model Hamburg of the well field Glinde. The fit of calculated hydraulic heads to measured hydraulic heads is exemplarily shown in five hydrographs (Figure 15).



Figure 15: Fit of calculated hydraulic heads to measured hydraulic heads in five hydrographs (Consulaqua, Hamburg Water).

The model has been commissioned by BSU and Hamburg Water and developed under subcontract by Consulaqua a private consultant. Hamburg Water is custodian of the model but BSU has free use of the model for internal purposes and any amendments to the model are jointly agreed upon. At present the intention is that the groundwater model might be used by Hamburg Water and BSU for decision and policy-making.

The inter-organizational working relationships have been a key in developing a fully integrated environmental model of the Hamburg urban area. The set-up of the ministry (BSU) means that those responsible for urban planning, water resource regulation and geological assessments are all part of the same organization and in addition Hamburg Water, the water company is state-owned. As a result, data and expert information is passed more freely between parties, datasets can be assimilated and derived products, models and model outputs can be used freely for decision-making. So while it has taken more than ten years to rationalise the urban networks and generate consistent models and while there are still some issues with data management, the benefits are clearly evident in the application of the models.



Figure 16: catchment areas of Hamburg Water well fields

Applications of groundwater modelling:

- 1. Develop regional water-balances and assess regional groundwater flow.
- 2. Assess hydraulic connectivity between shallow Quaternary and deeper Tertiary aquifers.
- 3. Assess the impact of new licensed supplies in the context of the regional groundwater system.
- 4. The increased use of the deeper underground warrant the development of source protection zones for the public water supplies from the Tertiary aquifer.
- 5. Optimization of groundwater and surface water measurement programs by using the results from the groundwater model.
- 6. Concepts for groundwater abstraction in catchment areas with instable salt-/fresh water boundary.

5 Conclusion

The creation and maintenance of a comprehensive database of regional geological and hydrogeological information for various aspects of land use planning in urban areas were considered for Hamburg as a crucial task. A growing population and an increase in trade and industry in a dynamically developing region have put a high strain on the natural environment and resources. As a result, mainly based on Earth Scientific aspects, precautionary measures have to be taken to protect the environment as well as implement steps to repair damage done in the past. Furthermore, requirements by the European Union such as the Water Framework Directive (EU WFD) are forcing planning authorities and developers to take into account the effects on the environment caused by developing activities.

One of the most important elements of successful urban planning is the availability of maps, documents and data. This material is providing the necessary basis for a survey of the area in question and its surroundings as well as further detailed information on the site. Collecting information about the subsurface already at hand is a task just as indispensable. It implies compiling and assessing available data from boreholes either for the exploration of groundwater or for ground investigation. It is vital that these data are easily accessible in a properly and adequately maintained database as well as process able with GIS techniques. In order to make those data available via the internet it is necessary to have standards for data format and transfer mode. In a national and international context, standardisation as to the exchange and storage of Earth Science data is vital and the main purpose of the INSPIRE directive of the European Union.

Generating a 3D geological model is probably the best way of getting an idea of geometry, distribution and spatial relationships within the relevant geological formation. Once such a model has been made, hydrogeological and geotechnical data as well as maps and plans can be added. Thus, a comprehensive model can readily be made available. High resolution 3D geology is providing a reliable basis for groundwater modelling in the City of Hamburg. Currently, a unified groundwater model for the area of Hamburg is set up to ensure the protection of groundwater resources.

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