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NATURAL ENVIRONMENT RESEARCH COUNCIL

COST Short-term scientific mission - Best practice for the monitoring and modelling of urban groundwater environments

Urban Geoscience

Internal Report IR/13/058

BRITISH GEOLOGICAL SURVEY

URBAN GEOSCIENCE

INTERNAL REPORT IR/13/058

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Keywords

Urban, groundwater, monitoring, models, cities.

Front cover

Model of central parts of Hamburg city © NERC 2013

Bibliographical reference

BRICKER, S H. 2013. COST Short-term scientific mission - Best practice for the monitoring and modelling of urban groundwater environments . *British Geological Survey Internal Report*, IR/13/058. 17pp.

Keyworth, Nottingham British Geological Survey 2013

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Acknowledgements

A number of individuals have contributed to the success of this short-term scientific mission and the collaboration between the cities of Hamburg and Glasgow. In particular we thank Renate Taugs and Lothar Moosmann at BSU Hamburg for hosting us in Hamburg and other members of the geological agency and water departments at BSU Hamburg for their time and advice. The local knowledge and experiences provided by colleagues at Hamburg Wasser are also greatly appreciated. Key staff at BGS including Diarmad Campbell, Dave Lawrence and Simon Price who have contributed advice and who have helped review the report are also thanked. The author thanks COST for offering the short-term scientific missions and for their financial contribution to the project.

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1 Introduction

The short-term scientific mission (STSM) to BSU Hamburg was part-funded by COST (European Cooperation in Science and Technology) and the British Geological Survey and informs the NAG-CITY and SUBURBAN COST initiatives. NAG-CITY is a partnership of Geological Surveys within the Northeast Atlantic Geoscience (NAG) group of geological surveys the aim of which is to make better use of the ground beneath cities. Two of the specific objectives of the NAG-CITY project are i) to better understand urban geology and ii) to gain a greater appreciation of the groundwater issues in urban areas and how best to resolve them.

A NAG-CITY workshop was convened in January, 2013 on Urban Groundwater Information Management at which 12 partner organisations from seven countries were represented. The aim of the workshop was to evaluate the current and up-coming urban groundwater issues encountered within the partner-cities and to look at how city-partners utilise hydrogeological data and information to address these issues.

The workshop highlighted the parallels in urban groundwater-related issues between the cities, where the impact of i) sustainable drainage schemes, ii) heat engineering systems, iii) flooding and iv) urban development on shallow aquifers are common concerns. The dichotomy in how groundwater data is collected, quality-assured, archived and served by city-partners was also evident. Where there is a high dependence on urban groundwater for public water supply, cities have established monitoring networks and standard procedures for validating and archiving data. Where groundwater is not used for public water supply in cities there has been little incentive to invest in formal groundwater monitoring networks and groundwater data that is available invariably comes from ad-hoc site investigations. The data available to regulatory authorities and environmental bodies was also largely dependent on the legislative requirements for data submission and reporting. There is however growing recognition of the importance of urban groundwater and shallow aquifer systems particularly in meeting the requirements of the Water Framework Directive (WFD) and in satisfying urban planning obligations. The following recommendations were proposed by the city-partners at the workshop:

- A greater awareness of potential groundwater issues is required by local government and developers at the city-planning stage.
- Best practice guidelines for urban groundwater monitoring for use by groundwater practitioners and those with an interest in groundwater should be developed.
- Standardised workflows, procedures and data formats for the collation, storage and servicing of data from both public and private bodies should be encouraged to maximise the quality, availability and re-use potential of groundwater data.
- The use of geological and hydrogeological modelling to support decision-making on urban groundwater issues should be considered in further detail.
- The significant uptake of geothermal heating and cooling schemes and the implications of this for urban groundwater requires further investigation.
- There should be a sharing of knowledge and experience between the city-partners.

Unlike some other European countries such as Germany and the Netherlands, urban groundwater monitoring in the UK is still in its infancy. Where specific problems have been identified, for example at large redevelopments projects; in London where rising groundwater levels have threatened subsurface infrastructure (Fry and Kelly 2008); or in Cardiff where the effect of the tidal barrage on groundwater was assessed (Heathcote *et al*. 2003), bespoke groundwater monitoring programmes have been instigated. However these schemes are largely ad-hoc, designed for very specific purposes and the mechanism for data archiving and re-use is non-standard. Systematic monitoring of shallow urban groundwater environments has not been implemented and there are no published standards or guidelines for urban groundwater monitoring.

BSU Hamburg, in collaboration with Hamburg Wasser, recently undertook significant work to rationalise groundwater monitoring within Hamburg, to reduce the number of monitoring points in the city; standardise the monitoring network and data captured; and, to ensure the network provides an appropriate density and frequency of monitoring data to address the key issues. This rationalisation of urban groundwater monitoring provides a 'Benchmark' example to COST about how other cities can target urban groundwater monitoring, identify key monitoring data requirements and use the data to answer specific problems.

BGS is currently undertaking a pilot study within the city of Glasgow, to assess how existing groundwater monitoring infrastructure, from individual regeneration and site investigation projects, can be used to develop a city-wide urban monitoring network. Work was undertaken to rationalise potential monitoring sites for the pilot network through the use of an integrated 3D geological – hydrogeological model to inform appropriate network design. The adopted approach is comparable to that used by BSU Hamburg.

The principles of better urban data collection, management and use developed within Hamburg are relevant not just for Glasgow but for other urban areas in the UK where there are similar drivers for urban monitoring and comparable geological environments.

This report summarises the findings of the STSM to BSU Hamburg in October 2013, evaluating the urban groundwater work undertaken and the relevant application within Glasgow and other UK cities. The report focuses specifically on i) urban monitoring networks, ii) the application of geological and hydrogeological models and iii) transfer of best practice to better understand urban groundwater systems. The issues identified within this STSM relating to data collation, data management systems and the technological requirements to serve data for onward use e.g. through data portals and web-interfaces is covered by Bonsor (2013) within an accompanying STSM report.

1.1 OBJECTIVES

The objective of the STSM was to gain an understanding of best practice urban hydrogeological/groundwater monitoring and modelling for policy-making. From initial data collection, evaluation and management, through to designing, installing and operating monitoring networks the aim of the STSM was to evaluate the best practice delivered by BSU Hamburg and consider relevant application within Glasgow and other UK cities.

Specific objectives:

- Evaluate urban groundwater monitoring requirements.
- Review the approach and techniques used within Hamburg to rationalise the groundwater monitoring network to meet current key monitoring requirements in the urban area, and to standardise data captured.
- Identify and begin to develop best practice guidance for meeting urban groundwater monitoring requirements from the Hamburg case study.
- Evaluate how urban groundwater monitoring data and knowledge can be used by the data provider and other end-users to address urban groundwater issues for policy-makers.

1.2 HOST INSTITUTES

1.2.1 Ministry of Urban Development and Environment (BSU, Hamburg)

The primary host for the STSM was BSU Hamburg, the ministry of Urban Development and Environment. BSU is comprised of several offices with responsibility for transport, spatial planning, urban renewal, sustainability, resource protection and waste management (Figure 1). The geological agency, the COST principle partner at BSU, resides in the office for Environmental Protection along with the water department who were also visited as part of the STSM.

The geological agency and the water department have been working in collaboration on the rationalisation of the urban groundwater monitoring network, generation of groundwater contours and conceptualisation and in the development of spatial hydrogeological datasets.

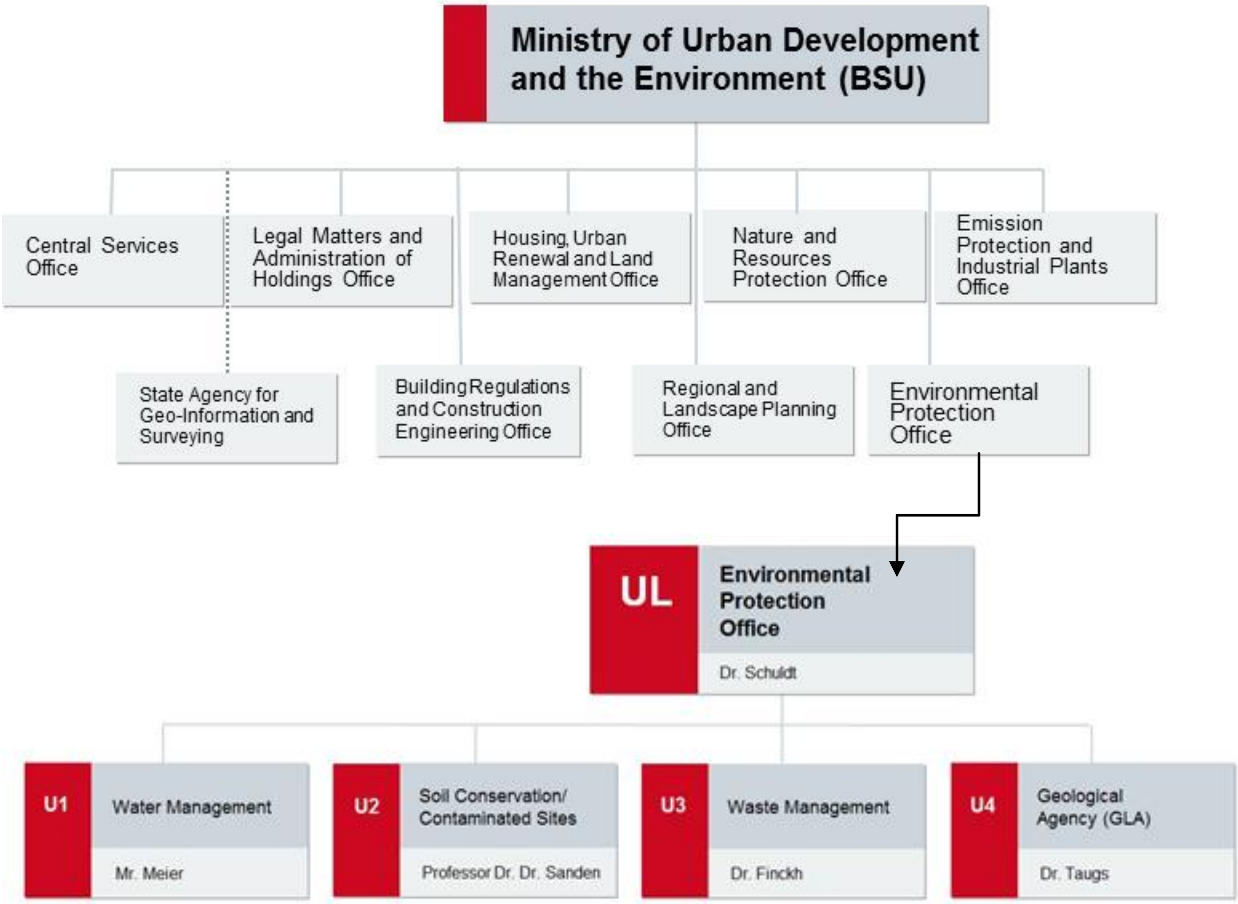

Figure 1 - Structure of BSU Hamburg, the Ministry of Urban Development and Environment (from BSU Hamburg, 2013)

1.2.2 Hamburg Wasser

Hamburg Wasser are the state-owned public water supply company serving Hamburg. Hamburg is entirely reliant on groundwater for public water supply with approximately 100 million m^3/yr water abstracted from 272 boreholes. Groundwater is abstracted from both shallow Quaternary deposits and the underlying Tertiary bedrock aquifers. In recent years Hamburg has invested a lot in water demand management and introduced charges for abstraction licences. Both initiatives have been successful in reducing water consumption in the city with water usage is significantly less now than 20 years ago despite an increasing population. The primary concern for groundwater resources in Hamburg is water quality, elevated levels of iron, manganese, nitrates and herbicides, saline intrusion, contaminated land and pollution resulting from sewerage treatment works.

1.3 ITINERARY

	Session	Institution	Institution contact
Tuesday	Drilling data, drilling data portal and groundwater data	BSU, Hamburg	Ingolf Stüven
	Monitoring network optimisation	BSU, Hamburg /Water Management	Lothar Moosmann (BSU); Water Management Team
Wednesday	Groundwater contours and monitoring network maintenance	BSU, Hamburg /Water Management,	Lothar Moosmann (BSU); Water Management team
	Wasserforum and waterworks	Hamburg Wasser	Jörg Grossman
Thursday	3D geological models and contaminated land sites	BSU, Hamburg	Jens Kroeger
	Urbanisation and climate change adaptation (RISA project)	BSU, Hamburg	Lothar Moosmann
Friday	Hamburg groundwater model	Hamburg Wasser	Jörg Grossman

2 Protocols for urban groundwater monitoring

With complete reliance on groundwater for public water supply it is necessary for Hamburg to implement extensive urban groundwater monitoring to ensure resources are protected. However it was recognised several years ago that the network was unnecessarily large, not all sites were yielding valuable data, the network was not targeted and it was expensive to maintain. In addition to the main monitoring network there are also monitoring networks maintained by Hamburg Wasser and the Port Authority. Without a complete overview of the monitoring sites in the context of the urban groundwater system there was concern that key monitoring sites could be lost and a more coordinated approach was needed. As a result BSU's geological survey and water department worked together to rationalise the network reducing it from >4000 potential boreholes down to 646.

Classification of monitoring boreholes:

Prior to rationalising 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. Geostatistical cluster analysis was also performed on all of the monitoring boreholes, across the hydro-stratigraphic units to assess relationships in the groundwater time-series data. While some differences were observed it was not possible to draw meaningful conclusions from the geostatistics so it was not used as a means to rationalise the monitoring network.

The rationalisation exercise focussed on the shallow Quaternary deposits for which there were the largest number of monitoring sites, reducing the network from 1054 boreholes to 539. 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 is more heterogeneous.

The Tertiary aquifer is more homogeneous and is better protected from potentially polluting activities by the overlying Quaternary cover requiring less groundwater monitoring. The Tertiary aquifer was not subject to the rationalisation exercise with the existing 109 monitoring sites of high quality and required to understand the groundwater regime. With an increase in uptake of deeper geothermal heating systems and with the prospect of shale gas exploitation the Tertiary aquifer is expected to be at increased risk and BSU are keen to ensure there is sufficient groundwater monitoring to assess these new threats.

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 i) areas of groundwater inflow to Hamburg, ii) areas susceptible to saline intrusion, iii) the area around the salt dome which lies beneath Hamburg, iv) areas where the groundwater levels are not overly affected by public water supply abstraction.

Criteria for rationalising the monitoring network within the Quaternary deposits:

- Boreholes completed within aquitards should be removed.
- Boreholes for which the construction and completion information is missing should be removed.
- Boreholes which are yielding poor quality data should be removed.
- A borehole separation of 500 m was implemented. The 500 m separation was derived on a trial-and-error basis whereby a separation greater than 500 m did not provide a sufficient level of detail in the derived groundwater contour maps. Where multiple boreholes were located within 500 m of each other the borehole with the best construction and highest quality data was selected by preference.
- Areas where the distance between groundwater monitoring sites exceeds 2 km have been highlighted as areas where the monitoring network needs expanding, though there are few areas in Hamburg where this is the case.

Monitoring frequency:

Prior to the rationalisation exercise monitoring boreholes in Hamburg were dipped manually twice a month. This monitoring protocol was deemed to be labour-intensive and not cost-effective. Now most sites have data-loggers installed which are downloaded 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.

Responsibility for the network and monitoring data:

Whilst the geological agency and the water department worked collaboratively to rationalise the monitoring network and the geological agency provide on-going geological expertise, overall responsibility for the network lies with the water department. As custodians of the monitoring network they are responsible for:

- 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 water quality site every 5 years, including CCTV inspection, pump test and geophysical logs.
- Ensuring all data from the main monitoring network and ancillary networks (e.g. Hamburg Wasser 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.

Generation of groundwater contours:

One of the primary uses of the monitoring network data was to generate groundwater contours for the Quaternary aquifer. There are insufficient monitoring points in the deeper 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, harbour 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 and minimum groundwater level contours have been generated in addition to contour maps for key specific time periods.

3 Modelling urban groundwater environments

3.1 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 based on mapping at the 1:50 000 scale. 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-divisions units have been amalgamated or subdivided based on their hydrogeological properties. For example Tills were combined to form one hydro-stratigraphic code. This approach differs somewhat to those used in the UK whereby a direct translation from geological unit to e.g. aquifer designation is applied. In the UK, definition of hydro-stratigraphical units for process modelling is done ad-hoc and by local agreement and varies between different models. The hydro-stratigraphy classification has been used to assign the boreholes of the groundwater monitoring network to the correct aquifer unit and has informed the groundwater modelling exercise.

3.2 3D GEOLOGICAL MODEL

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 only. 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 using the GOCAD software. The model primarily uses the coded borehole records to extrapolate 3D volumes of the geological units. A significant number of interpreted cross-sections exist for Hamburg (Figures 2 and 3); these cross-sections are not used directly in the GOCAD calculation but are imported into the GOCAD project to cross-check the model outputs against the cross-sections. Helper boreholes, based on the cross-sections, are added to the GOCAD model where the calculation doesn't capture the geology correctly. The cross-sections and the publicly-funded coded boreholes are freely available online (http://www.hamburg.de/bohrdaten-geologie). Private borehole records are not open to the public. The 3D geological model has been used directly in the groundwater model.

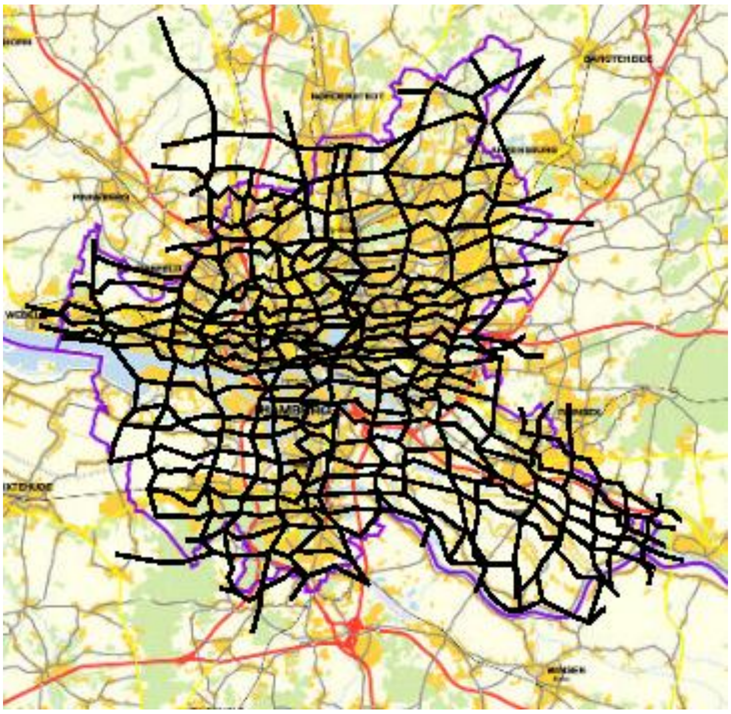

Figure 2 - Map of Hamburg urban area showing the locations of the interpreted geological cross-sections. Source http://www.hamburg.de/bohrdaten-geologie

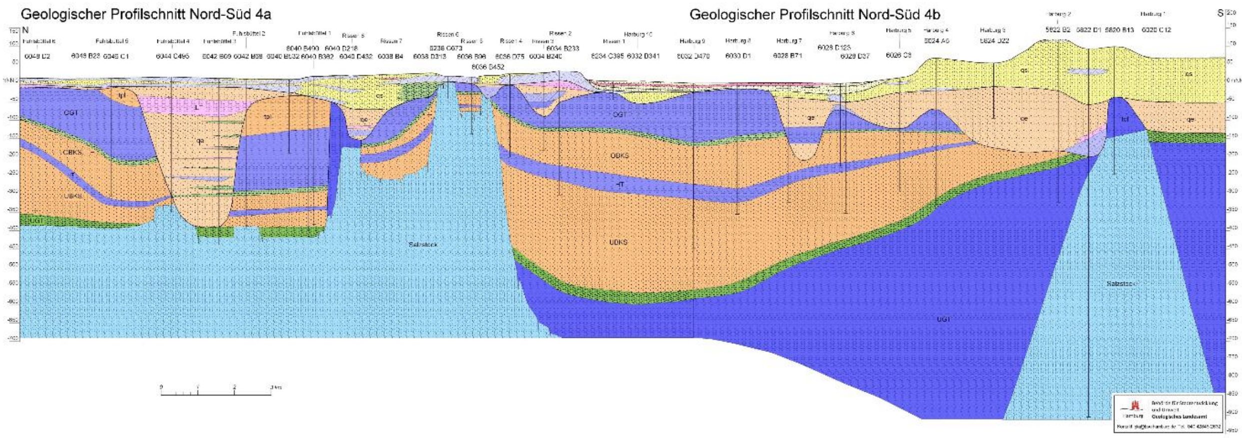

Figure 3 - Example interpreted geological cross-section, drawn N-S through Hamburg. Source http://www.hamburg.de/bohrdaten-geologie

3.3 GROUNDWATER MODEL

Coherency across the groundwater monitoring network, hydro-stratigraphy and geological model has facilitated the development of a unified groundwater model for Hamburg. Originally there were three regional groundwater models and a further five smaller-scale models covering Hamburg, each developed by different organisations 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:

- The increased uptake of deep geothermal heating systems and the prospect of shale gas exploitation warrant the development of source protection zones for the Tertiary aquifer public water supplies.

- An assessment of the impact of new licensed supplies in the context of the regional groundwater system is needed.
- To develop regional water-balances and assess regional groundwater flow and hydraulic connectivity between shallow Quaternary and deeper Tertiary aquifers.

The groundwater model comprises 16 layers covering the Quaternary and Tertiary units and has been developed using SPRING, a finite-difference modelling code. SPRING was used in preference to MODFLOW or FE-FLOW as its grid structure is better able to deal with irregular geological formations such salt domes, buried valleys and lenses where layers requires sections of zero thickness. The other added benefit of the SPRING software is that it allows 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 re-inserted to the regional model. The model code also allows flexibility in the layer thicknesses such that they can be adjusted easily as part of the model calibration process. STRING, a derivative of the SPRING code is used to carry out the travel-time modelling and define the catchment zones for the public water supply sources. Geological surfaces of the Tertiary geological units were defined using the 3D geological model and imported directly into the groundwater model. The Quaternary geology which hasn't 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. The groundwater model has been calibrated using the data from the monitoring network.

The model has been commissioned by BSU and Hamburg Wasser and developed under sub-contract by Consulaqua a private consultant. Hamburg Wasser is custodian of the model but BSU have free use of the model for internal purposes and any amendments to the model are agreed jointly. The intention at present is for the groundwater model to be used by Hamburg Wasser and BSU for decision and policy-making.

4 Transfer of best practice

4.1 URBAN GROUNDWATER MONITORING

Hamburg and Glasgow are cities of contrast when it comes to the level and extent of urban groundwater monitoring. However it is reassuring that both BSU and BGS have a similar approach to designing and reviewing monitoring networks. There is agreement that:

- drivers for monitoring must be clearly defined;
- boreholes should be assigned a hydro-stratigraphic unit;
- boreholes should only be adopted for monitoring if the borehole completion is known, the site is secure and the borehole yields high-quality data;
- the spatial density and frequency of monitoring should be appropriate for both the driver for monitoring and the hydraulic functioning of the aquifer.

Despite the parallels, there are some clear lessons for Glasgow and other UK urban areas. Consideration has been given to the hydraulic behaviour of the geological units in Glasgow but a formal hydro-stratigraphy has not been agreed with the city-partners. Agreement on the hydro-stratigraphy will direct groundwater monitoring to the aquifer units of highest priority.

Hamburg's groundwater level monitoring network consists of 646 boreholes whilst Glasgow's currently comprises just five. Consideration should be given to the minimum number of monitoring boreholes required to adequately assess Glasgow's groundwater systems and whether the investment for that level of expansion of the network exists. A depleted monitoring network yielding insufficient information for end-users is not cost-effective. Work in both Glasgow and

Hamburg suggests that the spatial independence for groundwater level variation in shallow Quaternary aquifers is of the order of 500 m – 1000 m which translates to a spatial density of approximately one borehole per square kilometre for city-scale groundwater level monitoring networks. While Hamburg is a large city, underlain by an extensive Quaternary aquifer, Glasgow by comparison is a more compact city and the primary aquifer units (the Gourock Sand Formation and the Bridgton Sand Formation) occur only along the main valley of the River Clyde. Assuming a spatial density of one borehole per kilometre less than 20 boreholes would be required for Glasgow's main urban area.

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 occur. Glasgow would benefit from a similar approach, by spatially defining areas of interest for the key groundwater issues the monitoring network can be more targeted and better designed. As a starting point the following zones should be defined; tidal influence, saline intrusion, shallow groundwater levels, known occurrences of groundwater flooding and key contaminated land sites.

4.2 MODELLING OF URBAN ENVIRONMENTS

BSU Hamburg and BGS have similar aspirations for full integration of observation data, geological modelling, hydrogeological conceptualisation and predictive groundwater modelling. Indeed successful application of urban geological and groundwater modelling is found in both Hamburg and Glasgow though using slightly different approaches. The benefit of Hamburg's approach is the collaboration between BSU and Hamburg Wasser such that a collectively agreed groundwater model will be used for the management of public groundwater resources and across the urban and environment regulatory functions at BSU. Decisions requiring a regional context such as the impacts of alternative energies and climate change on water resources can be made in a more defensible and open manner. Analogous collaborative modelling in the UK is rare; the Environment Agency's London Basin groundwater model is perhaps an exception whereby BGS geological modelling has been used directly and the water company – Thames Water are using the model for decision-making in addition to the Environment Agency.

Modelling of urban groundwater environments is challenging as it requires local-scale assessments to be applied at city-scales. Consideration of local-scale impacts such as land contamination, sustainable drainage options and impacts of sub-surface developments are required in addition to more regional assessments such as rising groundwater levels and climate change impacts. The heterogeneous nature of urban environments means that high data density more akin to individual site investigations and flexible modelling packages, such as GSI3D, are needed to capture the complexity of Quaternary and artificial deposits in sufficient detail to consider the local-scale effects. To be successful in urban modelling in the UK we also need novel mechanisms to capture local-scale data such as the GSPEC initiative in Glasgow (Barron et al., 2013). To fulfil the demand for urban groundwater modelling in the UK urban monitoring networks should form nested networks within wider regional monitoring networks, preferably with one custodian. The ability to capture multi-scale geological interpretations within 3D geology models already exists (e.g. in GSI3D) and groundwater modelling is moving towards linked multi-scale models.

4.3 INTER-ORGANISATIONAL RELATIONSHIPS

The inter-organisational working relationships in Hamburg have been key to 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 organisation and in addition Hamburg Wasser, 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 have taken more than 10 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. The same is not true in the UK where urban environments are controlled by one or more local authorities and by environmental regulators, geological expertise resides with the BGS and water resources are supplied by both private and publically owned water companies. Each of these organisations is responsible for the collation of different datasets and the enforcement of different regulations, each has its own funding and charging mechanisms and the means to share or licence data and models between the organisations is confused. So whilst there is often willingness for collaboration there are additional practicalities that must be overcome in the UK that don't exist in Hamburg. It is only through the implementation of specific initiatives such as NAG-CITY that all urban city-partners are granted a legitimate reason to invest time in collaborative activities. Increasingly, the mode for collaboration involves not just the exchange of data but also of expert knowledge; this has been successfully executed in Hamburg and is being initiated in Glasgow.

5 Future collaboration and outputs

Best Practice Guidelines

Hamburg provides an exemplar for European, urban city-scale groundwater monitoring and rationalisation of monitoring networks targeted to drivers. Together with BGS who are developing a new urban groundwater network for Glasgow, BSU Hamburg is well-placed to develop best practice guidelines for urban groundwater monitoring. Guidelines should cover both urban areas for which monitoring is in its infancy and cities for which monitoring is well-established but not necessarily targeted.

Peer-reviewer

BGS is in the final stages of writing a peer-reviewed publication on urban groundwater monitoring. The paper would benefit from a review by BSU, Hamburg to ensure that the paper is relevant to the European community not just the UK and to ensure that the recommendations are in keeping with views held by those running established monitoring networks.

3D modelling

The visit to Hamburg highlighted BSU's use of GOCAD for 3D geological modelling of the Tertiary geology. BSU would also like to develop a 3D model of the Quaternary deposits but the heterogeneous nature of the deposits (e.g. lenses and discontinuous sequences) makes it difficult to model in GOCAD. BGS has extensive experience of using the GSI3D modelling software to create 3D models of Quaternary systems and are in a position to advise BSU on its suitability for their geology and to provide training in the GSI3D software. BGS are going to follow-up with this offer at the next NAG-CITY workshop in Hamburg in November 2013.

Spatial datasets

BSU showcased outputs from their (Rain InfraStructure Adaptation http://www.risa-hamburg.de/index.php/english.html) RISA project looking at urban adaptation to climate change. The work utilises a methodology whereby the downhole borehole geology, rather than the surface geology, informs the classification or typology; this approach may be useful to apply in certain geological environments of the UK for which there is good borehole coverage but where detailed 3D modelling has not been carried out, e.g. in buried valley environments.

6 Conclusions

City-partners in Hamburg provide an exemplar for collaborative activities on urban geological and groundwater issues. The success is manifest in the shared geological model and groundwater model which is used across ministry functions and by the water company for decision and policy-making. The ability to carry out collaborative research (e.g. RISA project) and develop thematic spatial datasets, e.g. infiltration potential and thermal property models are ancillary benefits of the urban groundwater rationalisation work. What separates Hamburg from UK cities such as London - where groundwater models have been developed using the BGS geological models - is that the exercise in Hamburg is a collaboration of expertise rather than an exchange of data across organisations. The cost to Hamburg was an investment of time and funds, over a 10-year period, to rationalise the monitoring and develop the models. Having invested in the models the cost to Hamburg now is the maintenance of the monitoring network, servicing of data and updating of models.

Glasgow and other UK cities are similarly positioned for such collaborative activities in urban areas based on the drivers, expertise and technological capability. The challenge for UK cities is to collate and serve urban environmental data and implement representative monitoring schemes. The Accessing Subsurface Knowledge (ASK) network in Glasgow and the development of GSPEC for the submission of site investigation data to agreed specifications goes a long way to addressing these issues and should be a mechanism for transfer across other urban areas in the UK. Inter-organisational relationships in the UK also require attention and may be a barrier to collaborative urban monitoring. Funded initiatives such as NAG-CITY and directed research projects offer opportunities for formal collaboration but framework agreements and policy change is needed for longer-term collaboration.

The BGS strategy calls for greater sensing of earth systems through real-time monitoring and BGS and other NERC centres are keen to develop integrated rural-urban observatories. The opportunity exists for urban groundwater monitoring networks to form nested networks set in regional systems allowing local-scale city issues such as sustainable drainage and abstraction impacts to be assessed in the context of regional-scale issues such as climate change effects. Multi-scale geological modelling is already being implemented by BGS and linked multi-scale groundwater modelling technologies under development e.g. in the Thames Basin. These multi-scale approaches to modelling should be underpinned by multi-scale real-time monitoring networks.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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