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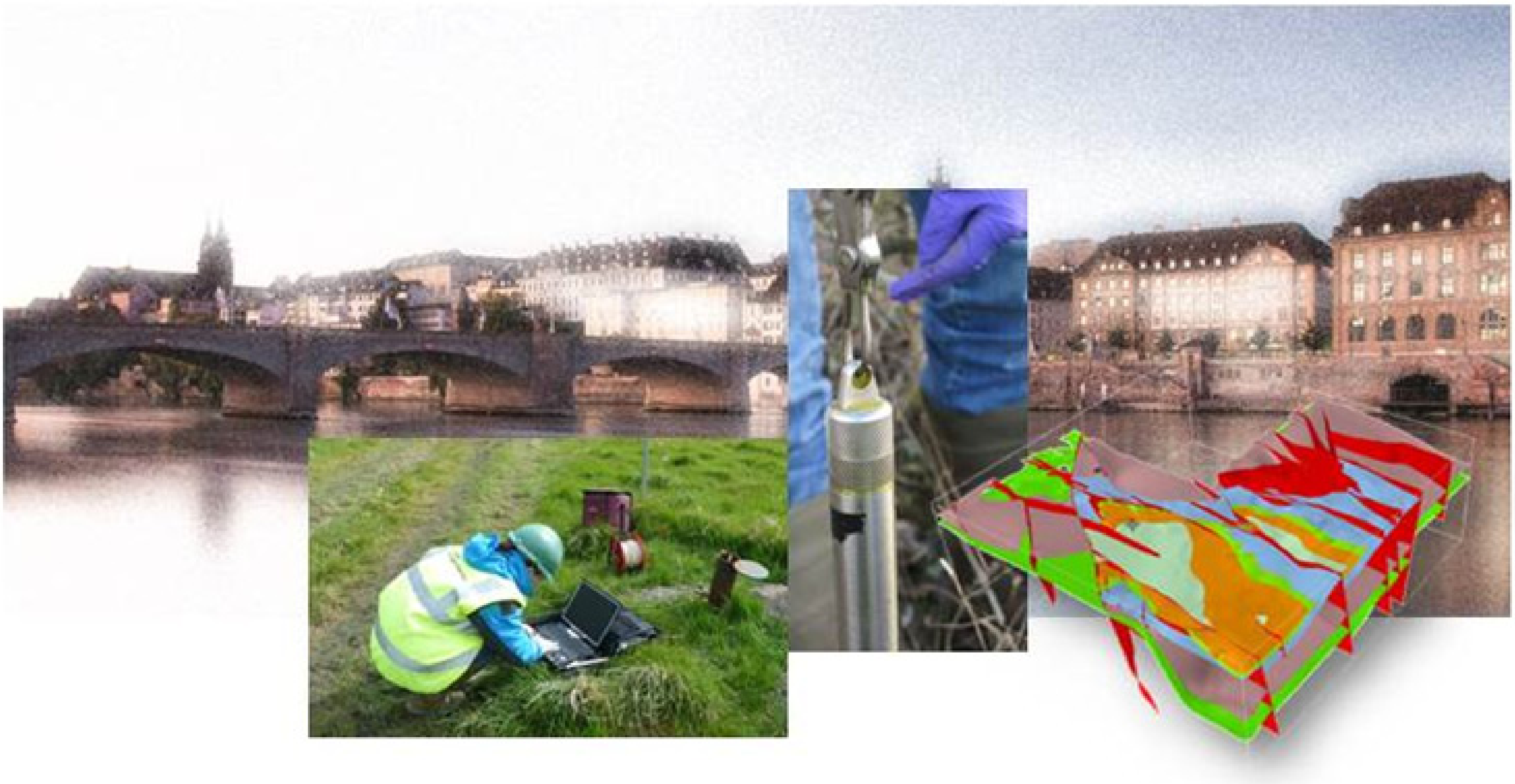

Groundwater, Geothermal Modelling and Monitoring at City-Scale

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Reviewing European practice and knowledge exchange

TU1206 COST Sub-Urban WG2 Report

H.C. Bonsor, P. Dahlqvist, L. Moosmann, N. Classen, J. Epting, P. Huggenberger,
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TU1206 COST Sub-Urban Report
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Contents

Executive Summary

The need for cities to make more effective use of the subsurface on which they stand, is increasingly being recognised in Europe and further afield to be essential for future cities to be sustainable and more resilient [1,2]. However, city planning worldwide remains largely 2D, with very few cities having any substantial subsurface planning or Masterplans – the cities of Helsinki, Montreal, Singapore being rare exceptions [3,4]. The consequences of inadequate consideration and planning of the subsurface are far-reaching, in economic, environmental and social terms. Across Europe, poor understanding of ground conditions is recognised as the largest single cause of construction project delay and overspends [5]. Management of urban groundwater and shallow geothermal energy resources is becoming increasingly important as cities are increasingly looking to use these resources to meet current and future energy and heating and water needs. Whilst these are, alongside potential underground building space, the two most important resources for future cities, the monitoring and regulation of these resource is widely variable across Europe.

For subsurface opportunities such as groundwater and geothermal energy to be realised and utilised to greatest effect to support growing city populations and infrastructure, city planners must be both aware of, and have some understanding of the resources, available data and research, and both the opportunities and risks which the resources provide to city development [6,7]. To supply this understanding to city municipalities and others, geological surveys must have robust datasets of groundwater and geothermal resources at city-scale, and the relevant knowledge and understanding from these data must be made accessible to inform subsurface planning in appropriate datasets relevant to different scale of interest in different planning stages. What density and frequency of data are required for a robust understanding of a city's groundwater and geothermal resources will be different in different cities, according to the complexity of the resources, and the intensity of subsurface use and demands on the resources. Indeed, no one design of city-scale monitoring or modelling of ground-water and -heat resources is appropriate for all cities, or for all monitoring objectives. However, the guiding principles of good practice for developing robust city-scale monitoring, and datasets are widely applicable, as are the key principles for ensuring these data inform city planning processes.

This report provides an initial review of existing examples of current practices in Europe with respect to groundwater and geothermal monitoring and modelling, as a resource for other cities to learn from and build upon. The report also provides an overview of some of the different practices used for communicating groundwater and geothermal energy data and knowledge to inform urban planning and management.

Section 1 of the report provides an evaluation of different good practices for generating appropriate city-scale groundwater datasets and monitoring. Section 2 reviews the different good practices for the use, regulation, monitoring and management of shallow geothermal energy in cities. Section 3 provides an evaluation of different good practices for modelling groundwater and shallow geothermal resources in cities of high and low data availability. Finally, section 4 provides a discussion as to why integration of groundwater and geothermal data into subsurface planning is still a missing link in good practices within many cities. The review provides city examples, which illustrate the guiding principles, or key points, of the different good practices discussed. The review is not aimed to be a comprehensive review of all the good practices which exist across Europe – this is far beyond the scope and resources of the review. The review instead forms an informed starting point for subsurface specialists and city municipalities wanting to learn about good practices related to groundwater and shallow geothermal data and knowledge. The Sub-Urban COST Action toolbox will provide further guidance and examples when released in 2017.

1. Introduction

Helen Bonsor

1. 1 Rationale

The need for cities to make more effective use of the subsurface on which they stand, is increasingly being recognised in Europe and further afield to be essential for future cities to be sustainable and more resilient [1,2]. However, city planning worldwide remains largely 2D, with very few cities having any substantial subsurface planning or Masterplans – the cities of Helsinki, Montreal, Singapore being rare exceptions [3,4]. The consequences of inadequate consideration and planning of the subsurface are far-reaching, in economic, environmental and social terms. Across Europe, poor understanding of ground conditions is recognised as the largest single cause of construction project delay and overspends [5]. Management of urban groundwater and shallow geothermal energy resources is becoming increasingly important as cities are increasingly looking to use these resources to meet current and future energy and heating and water needs. Whilst renewable energy and water are two of the most important resources for future cities, alongside potential underground building space, the monitoring and regulation of the resources is widely variable across Europe.

For subsurface opportunities such as groundwater and geothermal energy to be realised and utilised to greatest effect to support growing city populations and infrastructure, city planners must be both aware of, and have some understanding of the resources, and their limitations and potential, and they can be best integrated into urban development processes [6,7]. To supply this understanding to city municipalities and others, geological surveys must not only have robust datasets of groundwater and geothermal resources at city-scale, but relevant knowledge and understanding from these must also be accessible to urban planning processes. What density and frequency of data are required for a robust understanding of a city's groundwater and geothermal resources will be different in different cities, according to the complexity of the resources, and the intensity of subsurface use and competing demands. Indeed, no one design of city-scale monitoring or modelling is appropriate for all cities, or for all monitoring objectives. However, the guiding principles of good practice for developing robust city-scale monitoring, and datasets are widely applicable, as are the key principles for ensuring these data inform city planning processes.

Currently there is a large disparity across Europe in the quality of datasets, monitoring and understanding which exists for urban groundwater and shallow geothermal resources in cities [8]. And regardless of the availability of existing data, very few cities in Europe have strong translation of subsurface data and knowledge to city planning, as a result of fundamental communication gaps between specialists. There is therefore a lot of value in learning from existing examples, so that other cities may build and develop on these across Europe. This is the overall purpose of this review, with a specific focus to the key subsurface resources of groundwater and shallow geothermal energy.

Existing monitoring and knowledge for city planning in Europe

Some cities have very good groundwater datasets and monitoring, and these data are transferred and utilised very effectively in city planning and management. Other cities have very good subsurface datasets, but weaker communication and use of these data in city planning processes. And in some cities there is little subsurface environmental data available, and planning processes often largely omit the subsurface.

Cities which have historically relied on groundwater (e.g. Hamburg, Germany) generally have the largest amounts of historical time series data to help inform understanding of the resources, and also to optimise monitoring for future city planning needs. The large number of monitoring points within these cities can be optimised to collate sufficient data to help manage new and emerging city issues – e.g. rising groundwater temperatures within increasing use of shallow geothermal heat schemes, or increasingly shallow groundwater levels from increased use of infiltration drainage schemes. In stark contrast, cities which have had little historical reliance on the urban groundwater resource (e.g. Glasgow, UK) now have very few groundwater data or monitoring infrastructure available. Data which do exist are localised (both spatially and temporally) and related to specific redevelopment projects in the cities. The need for monitoring in these cities is increasingly important as a result of increasing use of shallow geothermal energy to support increasing energy needs, as well as the need to manage groundwater resources to be a much greater degree to mitigate increased flooding issues with increasing rainfall intensity and variability, and the increasing use of infiltration drainage schemes. In these cities, conceptual modelling of the resources, and focused investigative pilot studies, is an important tool to help improve understanding of the basic characteristics of the resource.

The level of available data, and existing monitoring, in cities is also interestingly influenced by the level of understanding and awareness developed between subsurface specialists and city authorities and regulators in the cities. In cities where there is strong engagement and understanding to the relevance of subsurface resources and appropriate data are accessible to city planning processes there tends to be greater level of monitoring and data, as well as a greater demand for the data. In cities where there is lower data availability, there is often lower demand for new data, or use of the data in planning processes – i.e. the potential value of groundwater and geothermal resources is not known by city planners, and therefore, data are not demanded.

'Developing city-scale subsurface environmental data for future cities and integrated subsurface planning'

Development of a strong virtuous cycle of data and knowledge exchange therefore is seen to be essential for the development and use of appropriate subsurface environmental datasets, and it is the third key pillar to good practice – Figure 1. Instigating a virtuous cycle of data and knowledge exchange in cities which have lower availability of subsurface data becomes essential to provide the demand and monetary resources for better subsurface data and knowledge – both from public and private sectors. Conceptual models based on the few subsurface data available, have been shown to be an effective means for geological surveys to highlight what might lie beneath the subsurface, and the importance of having more data to begin to both utilise and manage the resources [7,8]. For cities with little existing subsurface data, conceptual modelling therefore forms a good practice.

Cities within European cover a large continuum of different practices. Few, however, have established good practices in effective communication and translation of these data and knowledge to city planning processes. Greater integration of existing knowledge and datasets of these resources into city planning is required in nearly all European cities, for their effective utilisation and sustainable management.

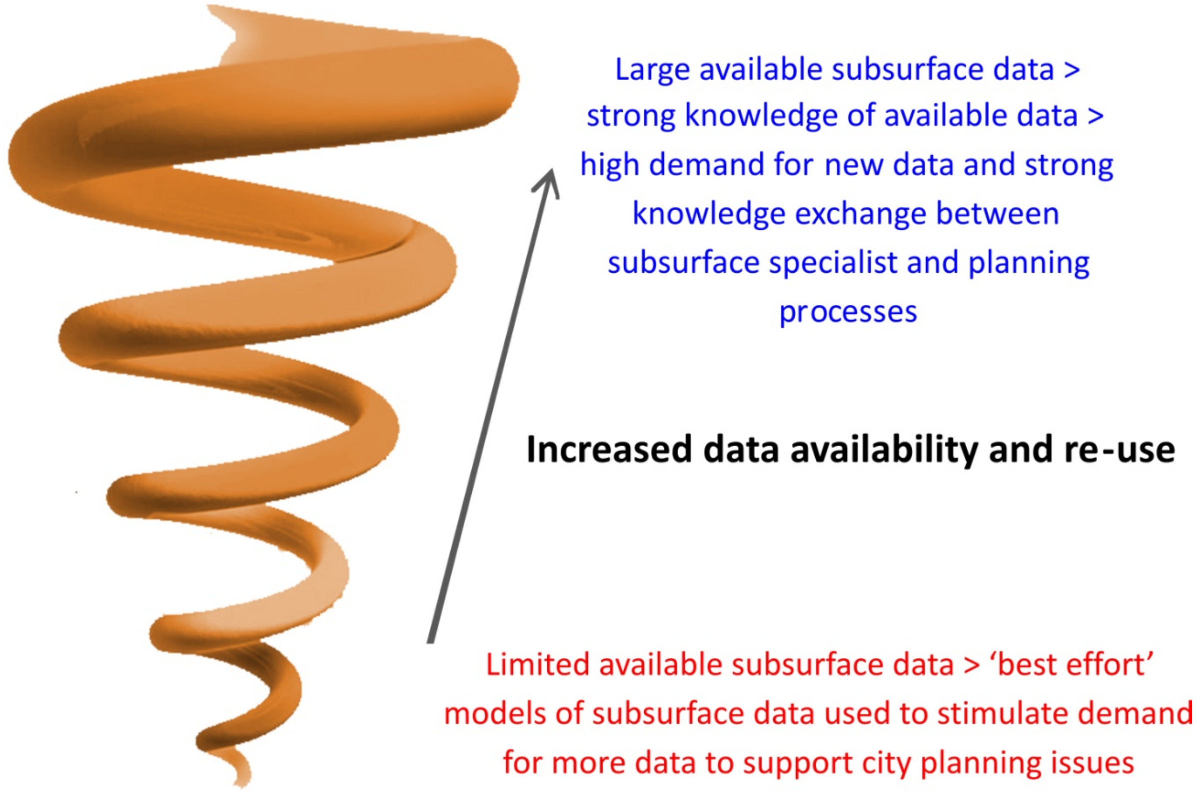

Figure 1 – Supply of subsurface data generates demand, and an increasing virtuous cycle of data and knowledge exchange.

1. 2 Report authors

This report has been compiled by a consortium of researchers and city partners from 8 countries within the COST Sub-Urban Action, and the report presents existing knowledge from universities, geological surveys and city municipalities. Leading city examples and research case studies are reviewed by the report.

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British Geological Survey
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Helen Bonsor is a Hydrogeologist and NERC Knowledge Exchange Fellow at the British Geological Survey, UK, and she is also chair of the IAH Urban Network. Her current work is focused to developing understanding on: what data and research are most relevant to city challenges; what training and capacity is required for relevant research outputs to be utilised within decision making processes; and to pilot and establish new processes of data and knowledge pathways between research organisations and stakeholders. Her other significant research interests and activities are focused on developing countries for large-scale characterisation of resources, and examining functionality of rural water supply.

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Deltares
Utrecht, Netherlands

Roelof Stuurman is specialist in integral management of environment, water and soil: hydrogeological systems analysis on a regional and local scale in support of spatial -, environmental- and water policy planning. Research is focused on the relation groundwater-surface water in the upper meters of the subsurface (water quality, water dynamics) and on research on seepage processes in relation to surface water base flow conditions, ecology and water quality. He has extensive experience of urban groundwater monitoring design and implementation in different urban contexts around the world.

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Senior researcher in department of Hydrogeology with professional skills in hydrological modelling (groundwater/surface water interaction, rainfall-runoff modelling, spatially distributed modelling, influence of global changes on water resources), remote sensing (classification of multispectral satellite images, extraction of vegetation information, LIDAR), GIS/Spatial analysis (natural vulnerability assessment, geostatistical analysis, 3D modelling). Participated in different international and national projects related to water management (INCOME- Improved management of contaminated aquifers by integration of source tracking, monitoring tools and decision strategies, ADAPTALP – Adaptation to Climate Change in the Alpine Space, Alp-Water- Scarce- Water Management Strategies against Water Scarcity in the Alps, Implementation of Water framework directive in Slovenia, TRANSENERGY – Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia).

Peter Dahlqvist
Swedish Geological Survey
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Peter Dahlqvist is a hydrogeologist and sedimentologist working at the Geological Survey of Sweden. His work involves a wide range of groundwater issues: groundwater mapping, valuation of groundwater aquifers, environmental objectives, shallow geothermal energy, groundwater dependent ecosystems, groundwater recharge from wetlands, etc. Ongoing research and mapping work includes airborne TEM investigations and 3D modelling of geology and aquifers.

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Odense City Municipality
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Gert Laursen is a geologist working within the city municipality of Odense, Demanrk. His work involves a wide range of experience in geological and groundwater issues with the city development and planning processes; and data and research required to unlock city challenges. His recent work has been part of the work to develop an integrated above and below city information model tool for Odense to support city planning and decision making.

Dr. Jannis Epting
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Jannis Epting performs basic and applied research at the Applied and Environmental Geology group at the Department of Environmental Sciences of the University of Basel. His work is related to regional geological and hydrogeological questions (e.g. groundwater flow, heat and transport modeling, determination of groundwater protection zones, well capture zones, nitrate transport and geophysical investigations of contaminated sites, consideration of subsurface heterogeneity).

Research and project work includes the management and protection of surface water and groundwater during the construction of major infrastructures in urban areas. This included the development and application of new methods for adaptive urban groundwater management and protection. His recent research focuses on the thermal management of unconsolidated shallow urban groundwater bodies and issues related to the heat island effect observed in many urban areas worldwide.

Prof. Dr. Peter Huggenberger
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Peter Huggenberger is head of the Applied and Environmental Geology group (Department of Environmental Sciences, University of Basel) and in charge of the Geological Survey of the City and the Agglomeration of Basel. He worked in different domains of adaptive management of groundwater resources in urban areas.

He is a scientific consultant for agencies at the municipal and state level regarding different aspects of groundwater and natural hazards. He has experience in aquifer sedimentology and in the acquisition and processing of geophysical data on fluvioglacial deposits. Recent projects include research on the impact of subsurface structures on thermal groundwater flow regimes. Within several interdisciplinary projects, Peter Huggenberger cooperates with European research institutions, among others the EAWAG and the Universities of Strasbourg, Tübingen, Stanford, UPC Barcelona and UFZ Leipzig. He is vice-president of the Swiss Hydrogeological Society (SGH) and member of the Swiss hydrological commission of the Swiss Academy of Natural Sciences.

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Ministry of Environment and Energy Hamburg (BUE)
Geological Survey, Hamburg
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Lothar Moosmann studied Geography and Hydrology at the University of Freiburg (1994). He then worked in various projects of applied hydrogeology and groundwater modelling. Since 2000 he has been working at the Geological Survey of Hamburg. His work focuses on hydrogeology, groundwater modelling, information and advice.

Nikolaus Classen
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Nikolaus Classen is a geographer and soil scientist in the Ministry of Environmental and Energy of Hamburg, Germany. He observe the groundwater quality and amount on the city scale of Hamburg by the use of a well-designed governmental monitoring system. Building on the results he develops GIS models to describe and visualize the water table or the chemical situation on city scale. Furthermore he implements the groundwater issues of the EU Water Framework Directive in Hamburg.

Alejandro García-Gil
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Alejandro García-Gil is a PhD Student at the University of Zaragoza (Spain) in collaboration with the Institute of Environmental Assessment & Water Research (IDAEA) in Barcelona. His research focus is on the development of thermal management policies and remediation strategies of overheated urban groundwater bodies due to unbalanced shallow geothermal activity in semi-arid climates. His approach is based in the numerical modelling of the processes originated in the subsurface as a respond to heat exchange from a physical and chemical point of view.https://www.researchgate.net/profile/Alejandro_Garcia-Gil

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Dr Gogu is a senior researcher with experience in hydrogeology, numerical modelling as well as spatial data analysis. His resume shows over 25 years of experience in groundwater modelling, groundwater vulnerability assessment, groundwater artificial recharge, geospatial databases design, and GIS-based geosciences modelling tools. This was achieved during different international projects, as working in different European countries: Switzerland, Belgium, Spain, Greece, and Romania. He is full professor and the head of the Groundwater Engineering Research Centre (CCIAS) at Technical University of Civil Engineering of Bucharest. Since 2011 he built up the Groundwater Engineering Research Centre (www.ccias.utcb.ro). The CCIAS team develops applications within several contracts targeting both private and public sectors (FP7, EEA Grants, European Space Agency, Swiss National Funds, local authorities and others).

1. 3 Report structure

Urban groundwater and shallow geothermal energy resources are becoming increasingly important for cities to meet current and future energy and heating and water needs. And, as demand and competing uses of resources grow, so too does the need for city municipalities and regulators to have sufficient understanding to protect and manage these urban resources effectively. There is a large range in the quantity and quality of datasets which exists for urban groundwater and shallow geothermal resources in cities [8]. And, very few cities in Europe have strong translation of subsurface data and knowledge to city planning, as a result of fundamental communication gaps between specialists. This report provides an initial review of existing examples of good practice in Europe in respect to groundwater and geothermal monitoring and modelling, so that other cities may build and develop on these across Europe. Key topics of focus throughout the report are the: the correct design of groundwater and thermal monitoring; the resolution of monitoring and modelling required for different purposes, and with different data availability; regulation; and, different good practices in Europe for communicating groundwater and geothermal energy data and knowledge to inform urban planning and management.

Section 1 of the report provides an evaluation of different good practices for generating appropriate city-scale groundwater datasets and monitoring. Section 2 reviews the different good practices for the use, regulation, monitoring and management of shallow geothermal energy in cities. It includes a review of existing drivers and barriers to geothermal use, as well as a brief review into different levels of Section 3 provides an evaluation of different good practices for modelling groundwater and shallow geothermal resources in cities of high and low data availability. Finally, section 4 provides a discussion as to why integration of groundwater and geothermal data into subsurface planning is still a missing link in good practices within many cities. The review provides city examples, which illustrate the guiding principles, or key points, of the different good practices discussed. The review is not aimed to be a comprehensive review of all the good practices which exist across Europe – this is far beyond the scope and resources of the review. The review instead forms an informed starting point for subsurface specialists and city municipalities wanting to learn about good practices related to groundwater and shallow geothermal data and knowledge. The Sub-Urban COST Action toolbox will provide further guidance and examples when released in 2017.

2. Urban groundwater monitoring: identifying good practice

R Stuurman and H Bonsor

Key words: city-scale groundwater monitoring; monitoring design; monitoring drivers; monitoring installation; groundwater monitoring infrastructure.

2.1 Introduction

This section provides a review of examples of good practice concerning city-scale groundwater monitoring, as wells as an overview of some of the key drivers for groundwater monitoring currently performed in urban areas in Europe. The section discusses key guiding principles for effective city-scale monitoring, comparing different approaches according to different drivers for monitoring, and pre-existing monitoring data and infrastructure in cities.

The saying “you can’t manage what you don’t measure” applies well to groundwater management. At the same time, measurement is useless without a vision of why the data is worth collecting and how it will enable improvements in groundwater management. Such a vision requires a basic understanding of the urban groundwater system. Why, how, where, when, and to whom is groundwater important?

There are a large range of drivers for groundwater monitoring, at city-scales. These include, but are not restricted, to:

- Need to understand the characteristics of the urban groundwater resource – this is typically found to be key driver for groundwater monitoring in cities across Europe which traditionally have not used, or managed the groundwater resource (e.g. cities which do not have issues with flooding and shallow groundwater-levels, and cities which have not historically used groundwater for drinking water supply)
- Need to protect the groundwater resource from over-abstraction and contamination – especially if used for public water supply
- Need to manage flooding (including flooding of building basements)
- Need to manage and redevelop contaminated soil and land
- Need to manage and regulate increasing use of shallow geothermal heat source schemes – both for heating and cooling – in cities

Understanding the depth to the water-table in a city, how this varies spatially and temporally, is essential for informed city planning, so that correct building foundation design is developed, there is appropriate use of infiltration schemes (i.e. they are not installed in areas where the depth to groundwater is less than 1 or 2 metres), and there can be informed utilisation and management of shallow geothermal energy schemes and private and public water supplies in an urban conurbation. Downstream impacts of the utilisation of these subsurface opportunities in parts of the city and redevelopment and regeneration schemes need to understood and incorporated into the wider above ground spatial planning work, to ensure utilise of the groundwater resource upstream, does need lead to negative downstream effects in other Strategic Development Frameworks in urban areas.

Cities which have historically relied on groundwater for industry or public water supply generally have a large amount of existing groundwater data and monitoring infrastructure at a city-scale. In these cities, the key work currently is to revise and systemise the monitoring network to be of an appropriate design and spatial distribution for current monitoring and data drivers, rather than historical drivers. Re-design and systemisation of city-scale groundwater monitoring network has been done very efficiently in Hamburg using the city’s 3D geological and groundwater models to meet the current drivers for understanding the groundwater resource (Bricker 2013).

In cities which have had traditionally very little historical use of the urban groundwater, the main aim of monitoring is to provide regulators and city authorities a general understanding of the characteristics of the groundwater resource – e.g. the depth to groundwater across the city – and how groundwater may impact flooding, building infrastructure, drainage and energy infrastructure. Installing a new monitoring network in these cities, which is appropriate to capture all the important variations in the resource, in the absence of significant existing, is fraught with difficulty. A pilot approach has been trialled in Glasgow and key lessons of good practice learnt from this which other cities can learn from.

2.2 Good practices

There is no one good practice for the development of city-scale groundwater monitoring – different data and monitoring network designs are determined by the city planning or regulator needs of the data collated, and also the complexity and variability (both spatially and temporally) of the urban groundwater resource. What is ‘good practice’ in monitoring network design and data sampling is very much dependent on the objectives of the modelling. Table 2.1 illustrates the range of different spatial densities of monitoring required for different drivers within the Netherlands.

Key guiding principles of good practice exist though. For example, it is essential that a monitoring network is developed for a clear objective – otherwise the data or understanding developed from the model will not be of an appropriate scale or resolution to inform the driver or objective behind the model. If there are multiple drivers for groundwater monitoring in a city, it may not be possible for sufficient data (either spatially or temporally) to be collated from one monitoring network. An example of this would be if city planning authorities wanted to collate data to understanding how groundwater is contributing to complex flooding issues across a city, and a water supplier wants to understand regional groundwater flow and seasonal water-table variations across the city. Either a nested monitoring network would have to be installed, so that the city planning authorities could collate more detailed data in some areas, or two separate city-scale networks would have to be developed.

Municipality	Main monitoring objective	Number of wells	outreach
Amsterdam	Protection wooden pile foundations related to leaking / draining sewers. Control high water levels.	> 3000 (6 times/year by hand), ca. 250 using sensors.	Public website
The Hague	Manage high groundwater levels. Takes action (drainage) when groundwater level exceeds 70 cm – surface level. Monitoring by hand every 6 weeks. City contacts complain owners within 3 days!	Hundreds.	Public website
Rotterdam	Wooden piles protection. No other specific objectives determined. Monitoring by hand.	Ca. 2000	Public website.
Gouda	Subsidence control and groundwater flooding	tens	Public website
Vlaardingen	Insight in risks of groundwater flooding related to land subsidence	hundreds	Public website
Breda	Groundwater flow patterns in relation to spreading of groundwater contamination	tens	none
Roosendaal, Bergen op Zoom	Insight in groundwater regimes, reference / aid in responding to complaints of citizens	60 – 80	none
De Bilt	Possibilities for infiltration of rain water in built up areas (disconnection from the sewer)	Ca. 40	website
Hoogeveen	Manage groundwater flooding	73 (all sensors)	Public website
Bloemendaal	Manage groundwater flooding due to stopped groundwater extraction and climate change	262 wells, 27 surface water level sites	report

Table 2.1 – monitoring objectives and density in a number of Dutch cities and municipalities.

In designing urban groundwater monitoring networks one must start at the back of the process: **the finished product.** What kind of information is needed, and how often should it be updated? Do you want graphs, tables, or other displaying formats? This amounts to an effective implementation of five aspects: (1) clear monitoring objectives, (2) data storage, (3) data analysis, (4) action plan, and (5) data presentation. Starting at the back,

> Data presentation: An urban (ground)water helpdesk requires some kind of periodical update of groundwater information in an accessible manner. Here we address three methods. Firstly, a groundwater annual report is a means to meet this goal. It is also an effective tool to grow groundwater awareness, both with the public and within the municipality. Groundwater awareness is crucial for the interpretation of the urban groundwater management, and therefore for a vital urban groundwater monitoring network. Secondly, displaying the results via the internet increases the visibility. A number of Dutch municipalities have already public groundwater monitoring websites: Amsterdam, 2500 locations measured 6 times/year and several hundred continuously (https://maps.waternet.nl/kaarten/peilbuizen.html), see Figure 2.1. The main groundwater monitoring objective in Amsterdam is protecting wooden piles in relation to damaged, and therefore leaking and sewer pipes draining groundwater: The Hague, hundreds of observation wells measured by hand every 6 weeks (https://wareco-denhaag-public.munisense.net/). The wells are distributed around the city, without specific objective; Utrecht presents in addition to the monitoring data also interpretations like isohypse-maps (lines with equal hydraulic heads). Thirdly, operating public groundwater observation wells can help to make groundwater visible. In that case the groundwater level can be read above ground using a recording output from a device which floats on groundwater in an observation well (figure 3).

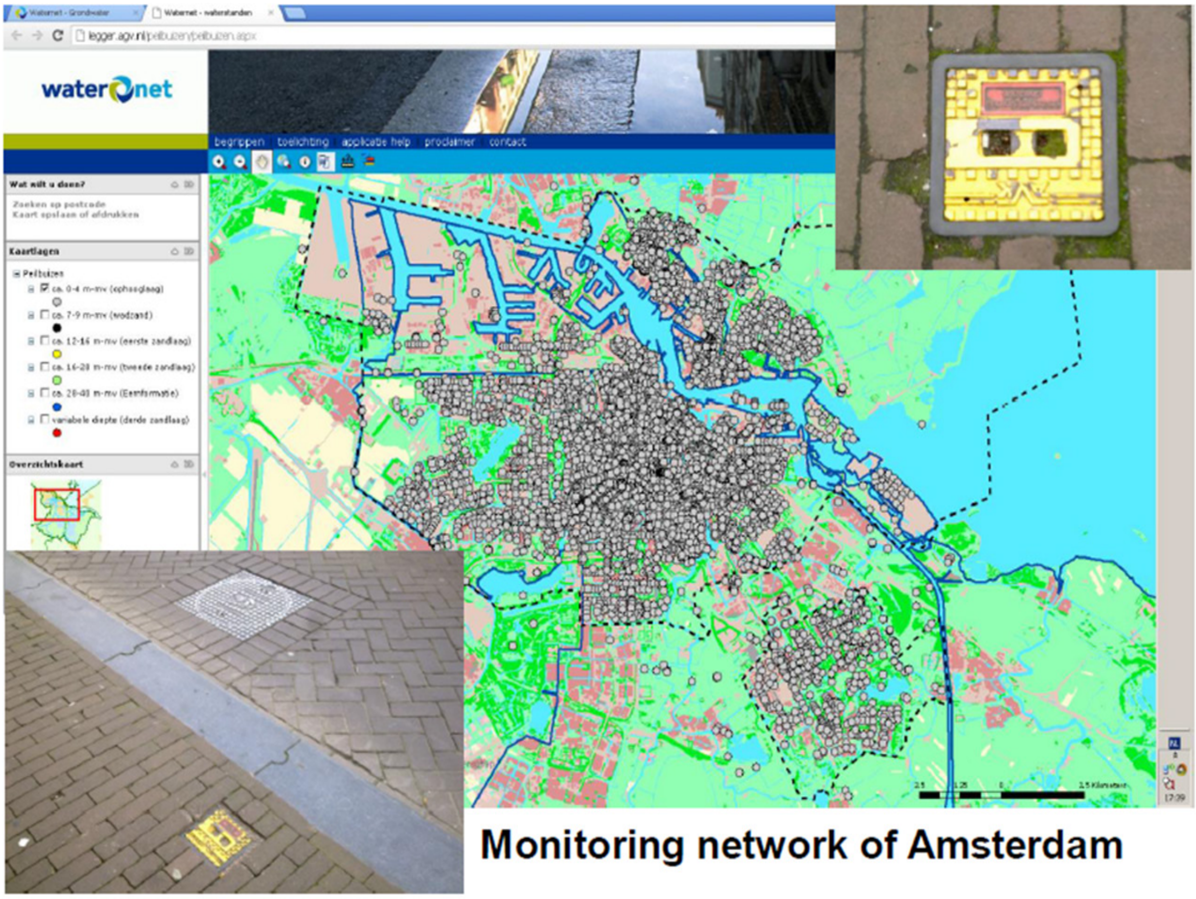


Figure 2.1: Internet map showing the observation wells in Amsterdam with photo's showing the observation wells in the streets.

Action plan. An action plan is essential for an effective urban groundwater monitoring network. The plan should comprise the monitoring variables determining whether action must be taken, signal and intervention levels, the type of action required, who is to take action and who is to pay for it.

Data analysis. The method of analysis depends on the measuring objective and the criterion on which action is to be based, e.g., a jump or trend in the groundwater level or exceedance of a certain value.

Data storage. Precious data require careful storage. The availability of long and consistent measurement series delivers a lot of information, e.g. about the effects of climate change on groundwater level fluctuation. The central Dutch DINO-database at TNO (www. Dinoloket.nl) includes all observation well measurements of provinces, water companies, water boards and a large number of municipalities. The measurements are stored, processed and presented in a uniform format, so that the dataset is immune for administration boundary reclassifications. The results are public accessible at Dinoloket, and now from the comprehensive national BRO database for all subsurface data in the Netherlands.

A dedicated monitoring network is designed for each objective individually. The dedicated networks can be combined into an integrated groundwater network.

Integration of the proposed objective-based monitoring networks leads to an integrated network consisting of shallow and deep observation wells. Different measuring targets determine each individually specific boundary condition to the monitoring network. For each observation well must be known what the measurement objective is. It is rare that all objectives can be served with one universal monitoring network.

Historically, many urban groundwater monitoring networks are the result of a steadily growing number of observation wells installed for project-related objectives (e.g. construction of infrastructure). Project monitoring networks are almost always clusters of monitoring wells. Only some of these observation wells should be included into a city-scale monitoring network infrastructure where they match with the general city-scale monitoring objectives. If a city-scale monitoring network incorporates all projects monitoring network infrastructure, the city-scale network will be too costly to maintain and operate, and it will also collate too much data, which is largely non-targeted to monitoring objectives at city-scale. Maintenance and operation costs of groundwater monitoring networks are easily and often underestimated, with tasks including, but not limited to: data collation from loggers and manual dipping; measuring point inspections; repair of incremental damage and tear; labelling; cleaning and purging of observation wells every few years; and water levelling checks every five years to update to absolute height of the tube and measurement datum.

Hamburg is good practice example of how monitoring networks can be reduced and systemised very effectively to match current monitoring data needs, and reduce operation costs (see section 2.4). Similarly in The Netherlands, where historically many municipalities have installed monitoring networks over time, a common concern is how to prevent a groundwater monitoring networks from becoming a costly investment that delivers little more than a collection of measurements where one hardly understands how to use these. This is becoming particularly pertinent following the substantial increase in the number of monitoring networks installed in municipalities following the 2006 groundwater duty-of-care legislation (Figure 2.2), and consequents shifts in monitoring requirements.

The need for monitoring arises from the need to successfully manage a resource or system. Monitoring is a cyclic process, where the kind of information needed determines monitoring strategy and design, enabling data to be collected, analysed, and translated into useful information. Besides being used for policy-making or operational management, monitoring results can also be used to refine the monitoring cycle itself.

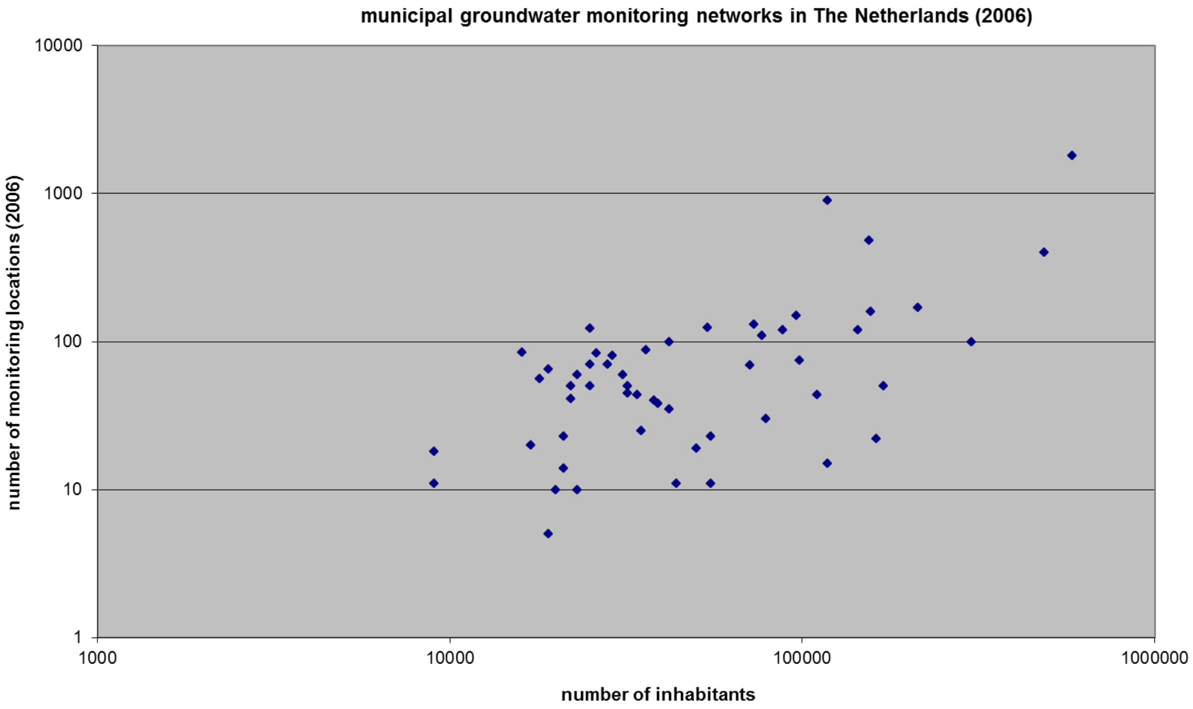


Figure 2.2. The number of urban groundwater monitoring networks, including used observation wells, in The Netherlands, prior to groundwater duty-of-care legislation (2006). Figures based on responses to a questionnaire (at about 1 observation well per 1000 inhabitants).

2.3 Workflows of good practice

Good practice in the **design** of groundwater monitoring network should include each of the following worksteps (the same worksteps are true for the optimisation of an existing monitoring work):

Identify the clear objective for monitoring, as the basis to the design of the monitoring network – i.e. the aquifer horizons to be monitored, the spatial density of monitoring and temporal frequency. Communication between different stakeholders with interest in the groundwater resource is essential here. If multiple drivers for monitoring, a nested monitoring network of varying spatial and temporal frequency across the city could be developed.

↓

State the minimum monitoring data required to be able to address the drivers for the monitoring. This can be determined by analysis of existing monitoring data, or groundwater data and understanding within a city.

↓

Identify monitoring data infrastructure available which could be adopted into the monitoring network – if of appropriate quality construction, and in appropriate aquifer horizon.

↓

Identification of spatial gaps in existing monitoring infrastructure

↓

Collation of all existing groundwater data (one-off and time series data) for the city from city-scale monitoring conducted by water supply companies, or public authorities, as well as available site specific data from across the city from site investigations, major redevelopment, and contaminated land remediation.

↓

Analyse existing groundwater data to assess spatial and temporal variability of groundwater levels across the city (and chemistry if data available).

↓

Collation of all other existing input for example geological maps, 3D geological models, looding data / maps, and location of abstraction well fields, private abstractions and underground infrastructure (if potentially below depth to groundwater)

↓

Show cost-benefit of monitoring to numerical modelling (When is modelling more cost-efficient or indispensable compared to analytical analysis of monitoring data or solely conceptual modelling approaches).

Statistical approaches and geo-spatial statistics can then be used to determine the minimum or optimum number of monitoring points required – both spatially, and within each aquifer horizon – to capture sufficient data to be able to manage the groundwater resource effectively according to the key drivers for the monitoring.

For the **installation** of monitoring points there are also some guiding principles of good practice as captured in the Ten Commandments box below.

Ten Commandments when placing monitoring wells

1. A measuring tube consists of a perforated part (the filter) and a blind dip tube. The larger the tube diameter, the better: 5 cm is common. The top of the filter must match the average highest water table; the bottom is at least half a meter below the average lowest groundwater level;
2. The average high and low groundwater levels can often be determined by soil characteristics. The zone under the average lowest groundwater level is always grey or when peat brown. Between the highest and lowest water levels are often rust stains. Unfortunately, these attributes are not standard documented at drilling reports;
3. Installation of monitoring wells in August or September reduces the risk of dry wells;
4. Keep in mind in case of clay or peat layers at what depth the measurement makes the most sense: below or above the disturbing layer or both. In the latter case, two separate drill holes need to be installed;
5. Recover perforations of disturbing layers with swell clay (bentonite). Add gravel (geochemical non-reactive) around the filter;
6. Prevent infiltration of rain water along the tube by using clay at surface level;
7. The top of the tube should be sealed with a perforated cap and a robust protective sleeve;
8. Make sure that the measuring location not too much stands out. Make a good location description;
9. Place the observation well not next to a tree or close to surface water, unless the measuring purpose this specific demands;
10. Has the contractor installed the observation well according to the design? A displacement of some meters can achieve the measuring purpose already seriously frustrating.

2.4 Case studies

Hamburg

Hamburg forms a key example of good practice in reviewing and systemising a city monitoring infrastructure to ensure the monitoring network is: cost effective to maintain and operate; and, the network design and data generated are appropriate for current monitoring needs

The key drivers for monitoring in Hamburg are to manage public and private water abstraction, so to mitigate flooding issues from shallow groundwater-levels which floods basements, and ensure protection of the water quality. Prior to the review of the city monitoring, the network consisted of over 2000s points.

Re-design and systemisation of city-scale groundwater monitoring network has been done very efficiently in Hamburg using the city’s 3D geological and groundwater models (Bricker 2013). The use of the models meant that the city municipality and key stakeholders (such as the public water supply utility company Hamburg Wasser) could work from an agreed conceptual model of the urban groundwater system, and identify where higher/lower monitoring density was required according to the location of public supply well fields, interaction of competing uses of the resource, and where there was greater geological and/or aquifer complexities (e.g. adjacent to the tidally influenced estuary river). This approach meant a complex task could be done very efficiently, without different stakeholder’s groundwater data (often held in different formats) having to be systemised and collated before the city analysis and review could be undertaken.

The 3D geological and groundwater models were used by the state geological survey (BUE) and public water authorities to determine the variability of the resource and the minimum resolution of the data required from the optimised monitoring network. Only 40 of the 650 monitoring points are required to supply sufficient data to meet the needs of the Water Framework Directive (WFD) – which only requires a general understanding of the resource.

Monitoring points were reviewed on the basis of their: construction quality (i.e. the boreholes were known to be properly cased and screened; the well-head had good sanitary seal); age; operation performance; and location in the aquifer (both spatially and vertically.

This led to the city’s monitoring network being reduced from over 2000 monitoring points of variable construction quality to just 650.

Glasgow

Glasgow provides an example of approaches which can be used to set up city monitoring networks in cities which have little historical groundwater data or city-scale monitoring.

The need for city-scale monitoring of the urban groundwater resource in Glasgow has arisen due to increasing issues of flooding; the need to be able to use infiltration drainage in the city where appropriate to alleviate the at-capacity sewer system; and to need to protect and mitigate groundwater quality in areas of contaminated soils in the city. The city municipality and the environmental regulator therefore have a need to better understand the general characteristics of the groundwater resource across the city (e.g. depth to groundwater; baseline quality).

There is very little historical groundwater data for the city of Glasgow, and the only recent data available are from very specific sites within the city where there have been major infrastructure projects, major redevelopment work, or remediation of large contaminated land sites. There is no city-scale monitoring infrastructure. To be able understand how shallow groundwater in the city contributes to flooding issues, and might restrict the use of infiltration drainage schemes in the city, city-scale monitoring data are required.

In the absence of significant groundwater data (point data or time series) developing an appropriate monitoring network design which would generate sufficient data was very difficult. Glasgow City Council and the geological survey therefore took another approach – developing a pilot monitoring network within a small area of the city centre where there is a large amount of existing groundwater monitoring data from site investigations, as well as 3D geological data and model. The pilot monitoring network was strategically designed so that groundwater-levels were monitored close to, and also away from the influence of rivers and infiltration schemes. The data and understanding of the groundwater resource gained from the pilot monitoring network was then used to assess what minimum spatial and temporal density of monitoring is required across the city. This knowledge can then be used to develop an appropriate city-scale monitoring network to develop a better understanding of the general characteristics of the resource.

In the absence of significant resources to drill new boreholes either by the geological survey, city authorities or national regulators, the approach being taken to develop the city-scale monitoring network is to adopt existing monitoring boreholes where available (and if of an appropriate location and construction quality) from specific sites and then install new monitoring infrastructure only where there are spatial gaps.

The application of the 3D geological information underpinned the design of the initial pilot monitoring network, and ensured a strategic and appropriate ‘pilot’ was used to inform a city scale design. Analysis of the groundwater monitoring identified that 1 borehole per 1.1 km^2 is required to capture significant temporal and spatial variations in the shallow groundwater to be able to characterise the general characteristics of resource at a city-scale.

2.5 knowledge gaps

ID	Current State	Desired State	Gap Description	Gap Reason	Remedies
1	Urban groundwater monitoring systems have been developed over time and are ad-hoc, and do not capture appropriate data for current monitoring needs	Systemised and optimised city-scale urban groundwater monitoring networks for individual city monitoring requirements and legislation	Lack of systemised urban monitoring	Lack of monitoring and networks and regulation. The overall responsible for arranging is not clear. Communication geologist-city planner must improve.	Monitoring, research, case studies, legislation.
2	No formal legislation or regulation on specification of monitoring infrastructure	Greater guidance and/or regulation of required minima monitoring infrastructure required	Limited urban groundwater monitoring legislative / regulative in some countries	Lack of recognition of importance of monitoring, and monitoring requirements. Difficulties in implementation in many cities due to lack of monitoring infrastructure	Monitoring, scientific work, case studies.
3	Lack of monitoring infrastructure and historical records in many cities	City-scale groundwater monitoring network and data collection to help inform city development opportunities and risks	Lack of systemised urban monitoring	Lack of finance, leglislation drivers in some countries, as well as lack of available monitoring data and research.	Investment, research, policy

3. Shallow geothermal energy in urban areas

P Dahlqvist, J Epting and P Huggenberger

Key words: geothermal urban environments; installation practice; monitoring practice; geothermal regulation.

3.1 Introduction

This section provides a review of examples of good practice concerning sustainable city-scale geothermal use, as well as an overview of the drivers and barriers to Shallow Geothermal Energy (SGE) use in urban areas in Europe. The section discusses both open and closed SGE schemes in different geological, hydrological, hydrogeological and urban settings. Regulation of SGEs in different countries is reviewed to provide an insight into some of the key requirements of SGE monitoring and modelling so that these are able to support effective management and regulation. Needs for cities with different characteristics is illustrated with examples from cities with high versus low data availability.

Range of city drivers and planning needs for urban areas

The use of SGE provides a large opportunity for urban areas to meet increasing energy needs in the future, and to increase the resilience of cities, with lower reliance on finite hydrocarbon energy resources. The use of SGE to supplement increasing energy demands of cities (in terms of both heating and cooling) can, however, place significant pressure on urban aquifers if exploitation of the resource is not effectively planned, particularly if there are competing uses of the groundwater resource. SGE use can lead to changes in: groundwater levels and groundwater quality. Elevating the temperature of the urban groundwater resource can also have wider environmental implications which impact city planning. For example in the Netherlands, rises in groundwater temperature and subsequent increased microbial populations in groundwater in some cities have led to significant decay of wooden building piles in heritage areas, leading to building subsidence. Considering the geological, hydrological, hydrogeological and operational boundary conditions and their interaction in urban areas, the situation is very complex. In view of the increasing demand for sustainable energy it is likely that SGEs will become even more frequent in the future. Urban planning in three dimensions is one of the keys to a sustainable use of sub-urban ground and groundwater resources (link to WG4).

Key planning needs in relation to SGE are:

- What is the “present thermal state” of different urban areas?
- What are the relevant “natural” and “anthropogenic boundary conditions which lead to the “present thermal state”?
- What is the energy potential for “cooling” and “heating demands” in different urban areas, also in context of the spatiotemporal availability of thermal resources (seasonal availability, storage schemes)?
- Can this energy be used to supplement district heating plans (i.e. is it economically and technically feasible to utilise the energy)?
- Would SGE use negatively impact existing uses of the subsurface and groundwater resource (interference with contaminated sites, subsurface structures as buildings and tunnels, ecosystems)?
- How many, and what density of SGE heat schemes can be sustainable in an area?

Range of SGE technologies

This report focuses on SGE, where ‘shallow’ in this context is < 400 m depth. Depending on the geology, energy needs and city planning there are several different types of SGE that will be best adapted for the specific environment. SGEs can be classified into Ground Source Heat Pumps (GSHP) and Borehole Thermal Energy Storage (BTES) and open systems Aquifer Thermal Energy Storage (ATES).

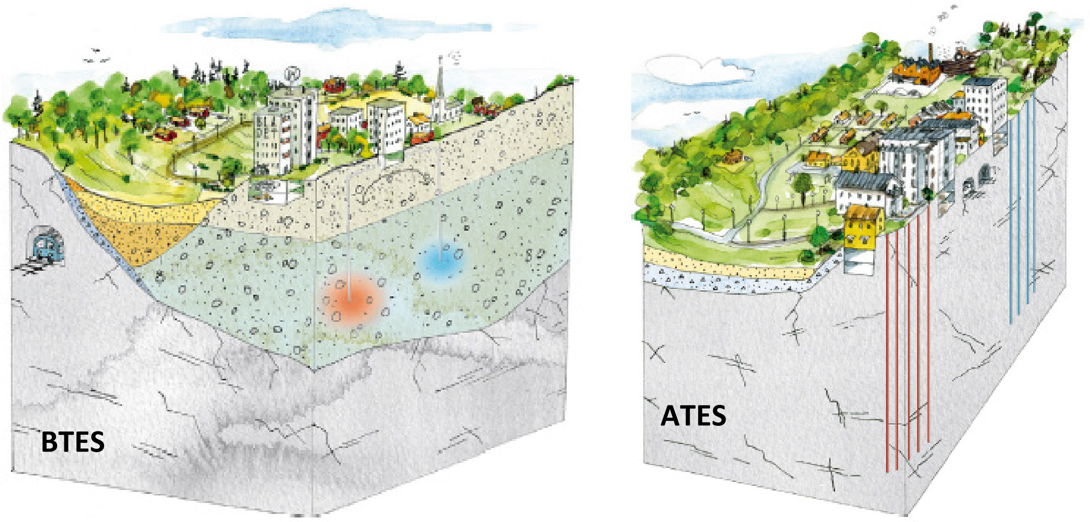


Fig. 3.1: Left: Borehole Thermal Energy Storage (BTES). Right: Aquifer Thermal Energy Storage (ATES) (redrawn from: Erlström et al. 2016).

Focusing for a moment on GSHP systems – there are two main types. The ground-coupled heat pump (GCHP) systems consist of a heat pump connected to a closed-loop network of thermally fused plastic piping that is buried in the ground. A water antifreeze solution is circulated through the inside of the pipe network transferring heat from the ground to the heat exchanger. No groundwater enters the pipe network; only heat is transferred by conduction to the refrigerant. Groundwater heat pumps

(GWHPs), the second subset of GSHP systems, directly exploit the significant heat capacity of groundwater. Using an extraction (or production) well, the water is conducted directly to the heat pump, where heat is added or removed from the water. The heated or cooled water is then returned to the ground through an injection well.

Ground Source Heat Pumps (GSHP) and Borehole Thermal Energy Storage (BTES)

In the closed systems, a heat transfer liquid, often a glycol-water mixture is circulating in a closed loop, and the heat energy is gained using a heat pump. The simplest and most common system are composed by a single or double u-shaped loop containing a heat transfer liquid which is installed in a vertical borehole, approximately 50 to 250 m deep (Fig. 3.1). GSHPs are mainly used for heating and cooling of small unit buildings (1 to 2 family houses). The BTES is a larger unit of GSHPs which is commonly used in apartment and public buildings with borehole fields with tens to hundreds of boreholes, often to a depth of 200-400m. In these systems the temperature in the underground is changed and can be used as a seasonal storage. BTES may be charged by e.g. solar energy during the summer period and used for heating during the colder part of the year (Huggenberger and Epting 2011).

Aquifer Thermal Energy Storage (ATES)

Open geothermal systems use the geothermal energy of the groundwater. In contrast to closed systems, the groundwater itself is the heat transfer liquid and the aquifer is used as energy storage. Such systems involve a pumping well to withdraw groundwater and a reinjection well where the used groundwater is reinjected into the aquifer after its thermal energy has been gained using a heat pump (Fig. 3.1). ATES systems are mainly operated by larger energy users (airports, department stores, hotels) for heating and cooling purposes. The direct use of groundwater as the heat transfer liquid represents a direct large-scale interference with the aquifer and the thermal groundwater regimes (Huggenberger and Epting 2011).

Geological environments of urban SGE use

Europe is a wide area with large differences in geology and the groundwater and SGE resources contained within these geological environments. Whereas "natural" groundwater temperatures should follow the regime of mean annual air temperatures in urban areas the Urban Heat Island (UHI) can be observed (e.g. Epting et al. 2013). Whereas, the groundwater mean temperature on a few tens of meter can vary between 2 to 20 °C between northern and southern Europe, and within cities where there are influences of subsurface buildings heat loss and multiple uses of the groundwater resource, groundwater temperatures can vary by 7 to 10 °C on a kilometre scale. Different geological environments present different opportunities and potential for SGE use in cities.

Consolidated sedimentary bedrock geology

Areas with sedimentary rocks are of great value for the SGE use. The porous media often holds sufficient groundwater resources that can be used. ATES solutions may be the best adapted SGE in these areas. In sedimentary rock environments there might be special conditions and formations that makes it difficult and sometimes dangerous to use SGE, like karstic areas and areas with salt and evaporates (Huggenberger and Epting 2011). These areas are very important to be mapped in three dimensions. Karstic areas with an underground conduit network and sinkhole development need careful attention. Evaporites may expand (swell) resulting in a considerable rock volume increase, and salt bearing formations may leach, which can lead to terrain uplift, respectively, or land-subsidence. Areas with sandstones and quartzite sedimentary rock make a good example where GSHP may be a well-adapted scheme, the high quartz content making it a very good heat transporter.

Crystalline basement geological environments

In the crystalline basement the most common and applicable SGE is the BTES solution, but GSHP solutions are also applicable depending on the urban setting and needs. The reason is that these rocks are less porous and the water is primarily transported in fractures. Fracture zones can be very important and graded drillings to use these zones are quite common. These graded drillings makes mapping even more difficult if not carefully reported to the authorities. Otherwise much of the heat transfer ability in these rocks depends on the mineral composition. Having a robust map of the heat transfer ability within a city or region, developing geothermal energy in these geological environments is therefore good practice.

Unconsolidated Quaternary deposits and buried valleys

In unconsolidated sedimentary environments the porosity and the water content (heat capacity and conductivity of the solid matrix and the fluid) governs the heat transfer ability. High water content is necessary and thereby the thickness of the deposits and the saturated zone is of high importance. ATES is the most common SGE solution in these environments. Information of sediment thickness, water table, flow direction, saturated zone, etc, therefore are important datasets from geological surveys or research organisations to help inform decisions of city planners. Good examples can be retrieved from Garcia-Gil et al. (2014) and Epting et Al. (2013) which discuss the geothermal management of alluvial urban aquifers by examples from Zaragoza and Basel, respectively.

Multi-layered groundwater aquifers – layered opportunities

When two superimposed aquifers are present they are often separated by an aquitard that makes them two different systems. This means one aquifer can potentially support water supply, and another geothermal energy use, without the two competing demands on groundwater resources coming into conflict. However, it is important the separating aquitard should not be penetrated more than necessary with drilling to ensure the two aquifers remain isolated. Any wells drilled to the lower aquifer should always be packed so that there will be no short-circuit, either of heat or pollutants, between the aquifers. The lower aquifer is often the one with higher quality groundwater and less endangered from urban risks. Therefore the lower aquifer should preferably be used for drinking water purposes and the upper for SGEs. It is important to know the depth of the boundaries of the different aquifers and aquitards, and their respective geometries. It is of great value if high quality data from well drillings can be arranged into a geological model to show these boundaries.

Interference of SGE use in urban areas with subsurface infrastructure and contaminated sites

SGE systems can interfere with existing subsurface structures as e.g. tunnels or sewage networks, which can be associated with considerable risks for urban subsurface resources as for the infrastructures itself. In areas with ongoing or abandoned underground mining there are a lot of special issues to be elucidated. First, there is a need of three dimensional mapping of mining infrastructure before any SGE-planning can take place in the area. The caverns may be a huge risk during drilling and different pressure levels of the groundwater may lead to problems with flooding of infrastructure or drawdown, sometimes leading to subsidence. Mining galleries act as fast transport route which may lead to pollution of the aquifers. If carefully examined, there are however opportunities too, the occurrence of underground waterways may be used for specially designed SGE systems.

An important foundation for SGE planning in urban areas is a three dimensional mapping of contaminated sites. Drillings, withdrawal, heating, etc from SGE systems may lead to a quicker and more extensive pollution in the subsurface. In Utrecht high-performance ATES is believed to remediate polluted groundwater resources and to account for a major contribution to an energy-neutral city by 2030 (see case studies).

Drivers and Barriers to SGE use in urban areas

Whilst SGE offers a significant potential to cities to meet increasing energy demands and decrease reliance on carbon economy, there has been a very disparate uptake of SGE in urban areas in Europe, due to different financial, political, and physical barriers and drivers to exploitation of the resource.

A report from the RE-GEOCITIES project (RE-GEOCITIES 2012) provides a review of the main *drivers* and *barriers* to SGE use in urban areas in Europe. Common drivers for SGE use are:

- government subsidies and financial profit incentives
- national renewable energy targets to which construction industry must meet
- private sector growth and investment in SGE technology.

The most common barriers to SGE use are:

- high installation costs of GSHP
- strict regulation of SGE use – time and cost, and high level of site investigation required
- crowded subsurface with competing uses, combined with a lack of information on the subsurface.

The RE-GEOCITIES project highlights clearly that having a clear and appropriate level of SGE regulation and legislation is critical to: the amount of uptake of SGE in a country and the degree of private sector investment in SGE; and, to achieving sustainable use of SGE, particularly in urban areas where there is the greatest opportunity and demand for SGE schemes.

Having too little legislation and regulation of SGE, leads to uncertainty and poor uptake and investment in SGE by the private sector. Countries in Europe which have the lowest use of SGE all cite the lack of clear regulatory and legatorial framework as being a key barrier to SGE exploitation, alongside:

- Low private sector investment in SGE technology
- Low level of knowledge of subsurface and existing subsurface infrastructure
- Different regional competencies within the country to understanding use of SGE
- Poor borehole data availability
- Lack of legislative drivers

Conversely, having too much legislation and regulation of SGE use, can also act as a barrier to SGE investment if the legislation and regulation incurs too much time (and therefore cost) to investors. A careful balance in legislation, regulation and planning permissions/licensing is, therefore, required to be struck to strengthen private sector investment in SGE and to ensure sustainable management of SGE, particularly in urban areas. Furthermore, legislations should be based on decisions which also consider long-term use of urban subsurface resources and a holistic view of the interference of different subsurface usages in urban areas, including e.g. those of quantitative and thermal groundwater use with subsurface structures.

Need for good practice

A wide range of approaches exists across Europe to harness and manage SGE in urban areas, in response to local opportunities, issues and subsurface conditions. Comparing these individual approaches enables general rules of key points of good practice to be identified for SGE use in urban areas.

There is a clear need for good practice in the use and management of SGE to ensure the SGE resource is managed sustainably alongside the many other competing uses (e.g. different quantitative and thermal groundwater uses and subsurface structures) of the subsurface in urban areas. In the future, a higher density of geothermal use will lead to unavoidable conflicts between neighbouring sites and other utilizations of subsurface resources (Huggenberger and Epting 2011), and the subsurface potential for different heating and cooling systems may be exceeded and affect groundwater quality (e.g. Possemiers et al. 2014). Moreover, in most urban areas, regulations for water resource management and geothermal energy use are currently sparse and often limited to the rule “first come, first served”. As a consequence, groundwater temperatures have increased significantly in some cities (e.g. north-western Basel, where groundwater temperatures reach seasonally up to 17°C (approx. 10°C long-term average annual air temperature)) (Epting et al. 2013). Indeed, the impacts of regional and local SGE use and groundwater exploitation are often orders of magnitude larger, particularly in urban areas, than any impacts of climate change (Epting and Huggenberger 2013).

The negative effects of SGE use can be minimised by effective management. This is only possible if there are sufficient hydraulic and temperature data that allow the urban thermal and groundwater regimes to the characterised at an appropriate resolution for city scale planning and regulation and risk evaluation. This enables the relation between groundwater flow and temperature regimes to be understood, and an appropriate level of SGE use planned or permitted within a city. A good practice of SGE planning is to provide suitability maps that enable a transparent approval practice for geothermal facilities, such as that developed in the city of Basel by Epting et al. (2013), who developed a thermal use concept for a pilot area in the Basel region on the basis of calibrated high-resolution heat-transport models. This makes the SGE potential and risk in different areas of the city understandable and accessible for city planning. It also provides guidelines on how risks associated with SGEs drillings can be minimized, and what monitoring methods and data are required to be collated to assist long-term sustainable management. Similarly the groundwater temperature maps developed for Berlin highlight regions suitable for SGE use and over-exploited areas, based on temperature data from 350 monitoring points across the city from 0 to 100m depth. (http://senstadt.3pc.de/umwelt/umweltatlas/eda214_07.htm).

3.2 Good practices

Key points of good practices for planning SGE use in urban areas

Before a permit for SGE use are granted every operator and permit authorities need a decision basis including:

- geological characteristics (sediment thickness, rock type, fracture frequency, porosity, permeability, heat transfer ability)
- hydrogeological conditions (groundwater levels, temperature, chemistry, flow direction)
- planned borehole depth, grading and distance to SGE points close by
- planned pumping rates and abstraction and re-injection temperatures
- information on conflicting interests, ecosystems, surface waters and subsurface infrastructure
- Estimation of the SGE resources susceptible of being managed

Several of these facts can often be collected by data mining, e.g. a lot of this data are available in company reports, at geological surveys, and unfortunately not systematically arranged in the same database. Although it will take time to produce an accurate database, it is convenient that such a work is compiled by the municipality or region. One example on an extensive compilation is the 3D spatial planning tool for the Basel region (Dresmann et al. 2013)

A good example on a thematic map that is possible to do with good material is suitability maps for geothermal use. In the Netherlands TNO has developed a public web-based information system called ThermoGIS that provides potential maps and also depth, thickness, porosity and permeability maps of potential aquifers in the Netherlands.

An example of SGE resources can be found in the Metropolitan Area of Barcelona (Spain) (García-Gil et al., 2015a). The automated calculation in the setting of a GIS platform has allowed the development of a multilayered 3D mapping of the low-temperature geothermal potential for GSHP exploitation systems, taking into account heat advection by groundwater flow.

A correct borehole construction and completion is crucial when the actual drilling and borehole is the highest risk in SGE systems. Guidelines for construction of SGE installations are necessary (e.g. Butscher et al. 2010). To increase the probability of a correct drilling it is important to use a certified operator. In nearly all European countries, drillers and contractors installing SGE schemes must be certified. In most countries, certification is at company-level, rather than individual drillers and certification is not legislated (RE-GEOCITIES).

Finally it is important to have comprehensive and established decision criteria for approval of SGE in the city. For the Swiss canton Basel-Landschaft a criteria based system was developed as a decision basis (Butscher et al. 2010; Huggenberger and Epting 2011):

Areas where SGE systems are not allowed

- Groundwater protection zone
- Contaminated sites
- Sites with competing subsurface usage (e.g. tunnels)
- Outside settlements
- Unit susceptible for heavy karstification
- Geological unit with the risk of rock swelling and sub-erosion

Areas where SGE are allowed with specific requirements (geological, hydrogeological and geotechnical clarifications)

- Groundwater protections area AU
- Area with the risk of karstification
- Area with multiple aquifer levels, confined artesian aquifers, saline aquifers
- Area with geogenic risks (landslides, oil shale, natural gas, rock swelling, subrosion)
- Area with insufficient geological information
- Capture zone of mineral or thermal springs

Areas where SGEs are allowed with standard requirements

- Other areas

Key points of good practice for monitoring and operation of SGE

During the operational stage it is important that data *are collated, shared and used for optimizing and securing the operation.* Monitoring of groundwater levels and temperature enables evaluation of the thermal groundwater facilities, making it possible to optimise operation schedules as well as extraction and injection locations. Monitoring data can also be used to develop, or incorporated into heat-transport models (hyperlink to WG 2.1 and WG 2.3) used by planners or city authorities and regulators to estimate the environmental impact and potential hazards on the groundwater resource (Butscher et al. 2010;

Huggenberger and Epting 2011). A good practice can be observed where there are several operators (water companies, city regulators and planners) who use combined monitoring programmes and models, such as in the city of Hamburg (Bonsor et al. 2013). Data that should be collated are:

- groundwater levels
- groundwater temperature (from top to bottom to get temperature profiles – and also upstream and downstream of the GHSP point)
- abstraction and re-injection temperatures
- pumping rates and volumes (extraction and reinjection sites)

A daily frequency might be proposed as good practice, but dependent on automatic recorders and monitoring equipment. Data should not only be retrieved from the production wells. It is necessary to have a representative amount and location for the monitoring wells both upstream and downstream which allow capturing the induced thermal impact of the individual SGE system. To get sufficient data for planning and management needs, a city may need to collate data from different sources, municipalities, geological surveys, operators, etc. and hence it is important, and a key point of good practice, that different operators collect the same monitoring data from different SGE schemes across a city, so the data can be combined within national or city databases (e.g. the national well database Jupiter in Denmark; http://www.geus.dk/departments/geol-info-data-centre/jupiter-uk.htm).

Key points of good practice relating to regulation of SGE in urban areas

New installations should be placed at an appropriate distance from surrounding SGE systems to ensure there is no interference between the systems, and the efficiency of individual schemes is maintained, and no long-term change to the groundwater temperatures have to be expected.

To minimise the impact of individual SGE schemes it is important to regulate:

- correct separation distances between SGE points
- temperature thresholds and acceptable thermal effect
- water abstraction quantities (for ATES)
- depth (may be site specific or where the Deep Geothermal Energy starts)
- the use of the same aquifer for abstraction and re-injection
- a registration system (to database, see RE-GEOCITIES, Database Handbook, 3.2)
- a monitoring reporting system (gives feedback to the permitting authority)
- areas where SGE is restricted (see 2.5)

Hähnlein et al. (2010) compiled the international status of the use of shallow geothermal energy. Regulation of these may be done in different scale, national, regional, or local levels; whereas requirements of detail depend on the geological and urban settings, conflicting interests and the SGE opportunity in the area. There is large disparity in legislation and regulation of SGE use in Europe (RE-GEOCITIES 2012). In almost all countries, legislation only extends to open SGE, and closed SGE are regulated to varying amounts non-legislatively. The Netherlands are one of the few countries, to regulate closed SGE using both separation distance and by temperature thresholds. Moreover, the permitted temperature change regulated by Dutch Law is one of the strictest in Europe – a change of +/- 1 ^{o}C being permissible. Abstraction and re-injection temperatures, both at the SGE point and in adjacent observation boreholes must be submitted to the regulatory authority. Most other countries regulate only on separation distances, and permissible temperature changes if regulated are much wider – +/- 5 to 7^{o}C being permissible generally, as long as the net balance per year is zero (i.e. SGE are used for heating and cooling over a year). In Finland you need a planning permission, since 2012, even for single loop closed systems in urban areas. The operator pays the municipality ca. 200 Euro to do a mapping and description of the area. The municipality collects all data in a database, in the city of Helsingfors there are now data from over 2000 SGE since 2012.

Good practices for thermal waste management

Thermal waste (Epting et al. 2013) occurs when there are excess or un-used high or low temperature groundwaters. Poor thermal waste management can lead to degradation not only of the groundwater resource, but also surface waters and ecosystems. To achieve a zero thermal gain/loss annually in the groundwater resource, excess energy can be injected into separate aquifers where there is a layered aquifer stratigraphy, or often it is more convenient to re-inject to the same aquifer, but ensuring equal annual heat addition and decrease – i.e. the aquifer is being used for both heating and cooling. To achieve this it is important to know groundwater and heat transport direction. The characteristics and distance to the downstream recipient is also important; a river may be influenced into a poor state if high or low temperature groundwater is entering and changing the local area. Different cities regulate different acceptable thermal annual changes, depending of other uses of the groundwater resource.

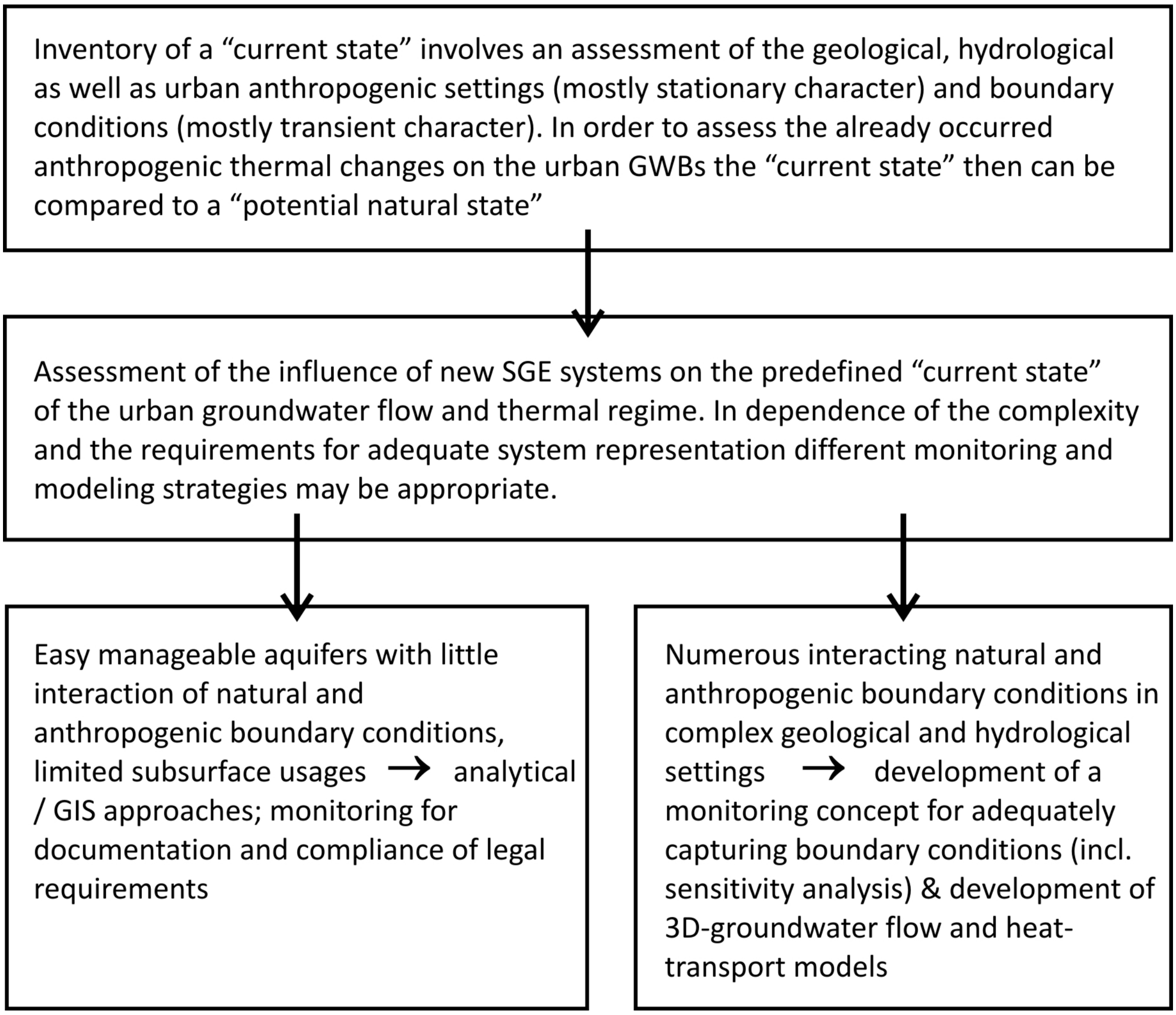
Remediation measures for the over-heated urban groundwater bodies

Robust remediation measures for the over-heated urban groundwater bodies of both cities include: (1) the use of groundwater for heating purposes and reinjection of comparably “cold” water to the aquifer; (2) artificial recharge of comparably “cold” surface water to the aquifer; as well as (3) seasonal storage of heat within the unconsolidated rock and underlying bedrock. Each of these measures and appropriate application of the measures are discussed in more detail by work within the cities of Basel (Epting et al. 2013) and Zaragoza (García-Gil et al. 2015).

These regeneration strategies would actively also reduce the temperature of groundwater exfiltrating into rivers, accommodating temperature thresholds formulated in some legal frameworks that also limit the use of shallow geothermal energy. For the investigated urban groundwater bodies of Basel and Zaragoza the use of groundwater for heating purposes would offer an economically auspicious alternative of resource exploitation. Thereby, shallow systems could be used for cooling and deeper systems (up to 400m) for heat storage (i.e. seasonal storage of heat in deeper geological formations).

3.3 Workflows of good practice

Good practice to assess the influence of SGE systems on urban groundwater flow and thermal regimes GWBs should include each of the following worksteps. This builds on work to develop good practice of shallow geothermal assessment in cities of Basel and Zaragoza (Epting et al. 2013; Epting and Huggenberger 2013; Garcia Gil et al. 2014). The same worksteps are also true for the optimisation of existing assessments, and can be directly applied:



Inventory of a “current state” involves an assessment of the geological, hydrological as well as urban anthropogenic settings (mostly stationary character) and boundary conditions (mostly transient character). In order to assess the already occurred anthropogenic thermal changes on the urban GWBs the “current state” then can be compared to a “potential natural state”

Assessment of the influence of new SGE systems on the predefined “current state” of the urban groundwater flow and thermal regime. In dependence of the complexity and the requirements for adequate system representation different monitoring and modeling strategies may be appropriate.

Easy manageable aquifers with little interaction of natural and anthropogenic boundary conditions, limited subsurface usages → analytical / GIS approaches; monitoring for documentation and compliance of legal requirements

Numerous interacting natural and anthropogenic boundary conditions in complex geological and hydrological settings → development of a monitoring concept for adequately capturing boundary conditions (incl. sensitivity analysis) & development of 3D-groundwater flow and heat-transport models

This stepwise procedure allows to approach new SGE systems in dependence of the complexity of the individual settings in different urban settings. Whereas practices range from simple mapping to applications of analytical solutions to simulate SGE impact in combination with mapping to high-resolution heat-transport modelling where numerous different subsurface usages come together.

3.4 Case studies

Defining a “current” and “potential natural” state of urban groundwater bodies

Basel (Switzerland) – The city of Basel and the work done by the University of Basel (Epting et al. 2013; Epting and Huggenberger 2013) provides a key example of good practice in establishing a robust understanding of how the anthropogenic influence of urban buildings, and shallow geothermal groundwater use has been affected the aquifer and groundwater resource. The work has specific emphasis to examining the effects of increasing building density and the urban heat island effect in the city, combined with increasing thermal groundwater use for cooling purposes and river-groundwater interaction affecting temperature patterns.

Existing and new monitoring network data were modelled to identify and characterize the seasonal and anthropogenic influences on the temperature regime of a study area within the urban groundwater body in Basel. The results derived from the investigated groundwater body allowed providing guidelines and a suitability map for geothermal subsurface use to the authorities across the city. Research work by Basel University (Epting and Huggenberger 2013) has enabled the potential natural state under undisturbed (pre-exploitation) conditions to be developed, from which different scenarios of groundwater use, urban development, and climate change can be modelled and understood, to help develop understanding of: the potential influence of climate change for the groundwater body in the urban area of Basel; and how the thermal groundwater regime developed before major urbanization of the region, and without thermal groundwater use.

Zaragoza (Spain) – Groundwater monitoring data, from a high resolution monitoring network in the city of Zaragoza has enabled highly effective management of the urban groundwater resource, and heat pump use, with natural river flood events which effectively cool the aquifer. There is a high level of shallow geothermal energy use in the city, and increasing concerns over the collective impact to raising groundwater resource temperature in the urban area, and the need to regulate and manage the thermal resource.

Modelling work, using the high resolution monitoring data, has enabled to strength of the hydraulic connectivity between the river and the groundwater resource, and the thermal impact seasonal flood events have to the groundwater resource. As a result of the understanding gained from this work, “cold” winter floods and the interaction with geothermal installations can be utilised by the regulators to enable enhanced thermal management of the aquifer.

This management of the resource is essential to enable increasing use of geothermal energy in the city, without negative impact. The work also highlights that such management of the resource, and utilizing natural flood events to mitigate anthropogenic impacts, requires a detailed and robust understanding of both the ‘natural conditions’ of the groundwater resource, but also the current impact of anthropogenic use. Understanding of the variable influences of hydraulic and thermal boundary conditions within an urban area specific geological and hydrogeological setting is crucial, for this level of management, and requires high resolution observational data and modelling capacity.

The high resolution monitoring network in Zaragoza has been developed from collaboration between the Spanish geological survey (Instituto Geológico y Minero de España, IGME) and the water local administration (Confederación Hidrográfica del Ebro, CHE). The modelling work has been led by the University of Zaragoza and the Institute of Environmental Assessment and Water Research (IDÆA-CSIC).

More information can be found on this work from the research publication by Garcia-Gil et al. (2014).

Approval process for new shallow geothermal exploitations in urban GWBs

Zaragoza (Spain) – In the city of Zaragoza (Spain), forms a key example of a first approach to standardize the concession process of new geothermal exploitation installations has been proposed (García-Gil et al. 2015b). The use of a groundwater and heat transport model and a specifically designed high resolution monitoring network for geothermal exploitation has favourably reproduced the evolution of heat plumes and thermal interferences in urban environments. This has allowed the development of a concession process protocol considering the evolution of heat plumes and thermal interferences in urban environments as a numerical water policy assessment initiative. The concession process protocol proposed takes into account: (1) sustainability which guarantees an energetically balanced system and therefore a renewable utilization of the resources, (2) legal certainty which guarantees the stakeholders investments and (3) equal opportunity which guarantees a fair exploitation of the resources.

High resolution monitoring for remediation, can enable optimization of thermal urban groundwater resource

Utrecht (Netherlands) – The urban groundwater resource beneath the city of Utrecht is polluted from different sources. Estimation is that 180 million m^3 groundwater is polluted with VOC's in an area of 700 ha. This groundwater is remediated by a combination of ATES and biological natural attenuation. Observation wells with filters at different depth to measure the impact of ATES on the contamination and a 3D glass-fibre network (http://www.fomebes.nl/het-project/partners/deltares/) for measuring the thermal spread of heat and cold is installed in the area. The fibre glass monitoring system generates a 3D picture of the energy balance in the subsurface which makes it possible to optimise the use of SGE in different areas. Similar projects are installed in Delft and Eindhoven. The results of the project will be available in early 2017.

3.5 Knowledge gaps

Some of the key missing knowledge gaps with respect to sustainable SGE use, and the planning of SGE use in cities are:

- How can a series of local water supply and thermal groundwater use systems be integrated into a network based on local and regional scale risk minimization, considering long- and medium-term development (development of groundwater and heat use concepts, suitability maps)?
  And, how can these complexities be communicated and included into city planning?
- To what degree can water-supply and thermal groundwater use systems be optimized?
- What thermal, chemical and microbiological effects occur downstream of thermal groundwater use and how can they influence future groundwater use?

ID	Current State	Desired State	Gap Description	Gap Reason	Remedies
1	The subsurface is used by several needs but in many cities too scarce monitoring and cooperation makes the use insufficient and unsustainable.	Use of the subsurface is coordinated and based on risk minimisation. Complexities are communicated and included into city planning, e.g. suitability maps and 3D-modells	Absence of integration of water supply and thermal groundwater use systems into a network considering long- and medium-term development.	Lack of monitoring and networks and regulation. The overall responsible for arranging is not clear. Communication geologist-city planner must improve.	Monitoring, research, case studies, legislation.
2	Water supply and SGE are using the same resource, but not necessary in the optimal way.	The subsurface including heat, cold and water supply is managed in an effective way	It is not clarified how and to what degree the water supply and thermal groundwater use systems can be optimised	Lack of monitoring data and research	Monitoring, scientific work, case studies.
3	In most cities there is a lack of monitoring data. The research results are not communicated or used in the cities	Thermal groundwater use does not restrict ongoing and future drinking water supply.	The thermal, chemical and microbiological effects occurring downstream of thermal groundwater use and how they influence future groundwater use.	Lack of monitoring data and research on effects.	Monitoring, scientific work, case studies. The correct data is collected and research programmes are developed.

4. Modelling urban groundwater and geothermal resources

L Moosmann and N Classen

Key words: city-scale modelling; optimisation; drivers; cost-benefit; data availability; modelling for regulation and management

4.1 Introduction

This section provides a review of examples of good practice concerning development and application of groundwater and geothermal modelling to help support sustainable utilisation and planning of the resources at city-scales. The review also includes discussion to costs and benefits of groundwater and geothermal modelling over investment in monitoring data and infrastructure in cities. Key future requirements in technical development and functionality of urban groundwater and geothermal models are also reviewed.

City needs for groundwater and geothermal modelling

Although groundwater is often referred to as a relatively stable and better-protected water resource compared to surface water (Volker and Henry 1988; Zektser and Everett 2004), the protection and management of groundwater is a complex task, even more so in urban areas where there are intense competing demands of the resource and surrounding subsurface. An understanding of natural hydrological systems and the processes of pollution transport form the basis for efficient water management is essential for appropriate groundwater management and planning in cities, as well as some understanding of the influence of urban infrastructure to the resource.

> *'Modelling is a helpful and essential tool to describe and understand especially the groundwater and geothermal processes on the City-scale today and also to predict future scenarios with different use of the resources.'*

The ability of city municipalities and stakeholders to simulate the natural system and scenarios of the impacts of proposed changes to the groundwater enhances the adaptive capacity of water management. A key use of groundwater modelling within urban areas is to assist understand develop these different areas of understanding, and to help delineate what groundwater protection areas should be within the more complex and heterogeneous urban environment. Other general drivers for the modelling include:

- Groundwater management (groundwater resources, groundwater use, catchment areas, groundwater-infrastructure interaction, remediation)
- Groundwater protection (contaminant transport, groundwater salinization)
- Thermal management (interaction of geothermal system, groundwater quality issues)
- Underground city planning (infrastructure development)

Different stakeholder prioritise some of the above drivers over others:

- Water suppliers (managing groundwater use, catchment areas, extraction concepts)
- Authorities (protection and management of groundwater, groundwater resources, shallow geothermal resources, sustainable development)
- Private (groundwater use, geothermal systems)
- City operators (water, transportation)

City municipality priorities are:

- How much groundwater can be sustainability abstracted without significant negative impacts to other city resources or infrastructure? (e.g. heritage building foundations, basement infrastructure, and soil and water chemistry?
- Does shallow groundwater influence flooding within the city, and if so in what areas?
- Where can infiltration drainage schemes be used sustainably in the city? And what at volume of water can be infiltrated?
- What are the impact of infiltration schemes to groundwater levels and flooding?
- What is the likely impact of proposed SGE schemes?
- Do new private abstraction schemes impact industry or public water supply schemes?
- Models need to accessible and understandable to city planning, so that the knowledge and data within them can be used to inform the planning process.

4.2 Good practices

There is no one good practice for the development of city-scale groundwater modelling – different modelling requirements are determined by: the end use of the model (which can be very different in different cities, according the underlying driver for development of the model); and, the availability of input data.

For example, a groundwater model being develop to help improve the conceptual understanding of the urban groundwater resource characteristics will have very different resolution and input data requirements than, a model being developed to inform a management of public water supply abstraction and defining well field protection areas. Groundwater models aimed at stimulating processes and problems of groundwater flooding will in turn have yet another modelling framework, and different set of priorities for the data and processes modelled and output requirements.

Good practice in model development is very much dependent on the objectives of the modelling and also the availability of input data.

Key guiding principles of good practice exist though. For example, it is essential that a model is developed for a clear objective – otherwise the data or understanding developed from the model will not be of an appropriate scale or resolution to inform the driver or objective behind the model.

Good practice in the construction and development of a model should include each of the following worksteps (Figure 4.1):

- **Identify the clear objectives for modelling**, as basis to design the conceptual or numerical model (communication between the contracting authority and the contractor and the interests of third parties or authorities). **State the minimum key input data required** and minimum amount/quality of these data (analysis of the available data, the framework for additional data collection and statements on how best to model quality that can be achieved with it).
- **Identification of knowledge gaps** and requirements for filling them (extension of groundwater and surface water monitoring systems; requirements on the documentation of groundwater use data and subsurface structures; definition of field investigations to study specific processes).
- **Show cost-benefit of numerical modelling** (When is modelling more cost-efficient or indispensable compared to analytical analysis of monitoring data or solely conceptual modelling approaches).
- **Identify valid modelling assumptions** (general acceptance in the model assumptions). Defining the requirements for the suitable setup of model geometries

(geology and subsurface structures) as well as necessary data for parameterizing the various natural and anthropogenic boundary conditions.

- **An agreed conceptual city-scale model by all users.** This avoids different users making decisions based on different conceptual and numerical groundwater models with different input data.

Guiding points of good practice for model accuracy and resolution of input data:

It is good practice to use input data and parameters of a scale and resolution only appropriate to the modelling objective. Some includes of input data which should be represented within groundwater modelling are listed. Not all groundwater models would have to include all of these data to be 'good practice', depending on the modelling objectives.

- Geology (drilling– cross section – surface map - 3D structure model; Geophysical data)
- Hydraulic parameters / pumping tests (hydraulic conductivity, storativity, permeability)
- Groundwater level data (hydraulic head, river and groundwater hydrographs, piezometric surface)
- Groundwater quality (pollution, salinity, temperature)
- Groundwater recharge (including water supply system losses), Interaction with surface waters and atmosphere (steady-state/transient)
- Infrastructure (water supply network, sewer system, tunnel, underground transportation network, subsurface building structures, permanent and temporary dewatering systems, district heating)
- Consumptive use of groundwater (pumping rates, demands)
- Geothermal use (pumping rates, production-injection temperatures, heat power)
- Transport parameters: Tracer test (solute) & thermal response test (heat) (porosity, dispersivities, molecular diffusion)
- Groundwater supply systems (pumping rates, exploitation schemes and schedules)

Input data required should be organized and made available in a database and/or GIS-system. At low data availability the limited data-sets should be supplemented by extensive data research. The available data widely open in a database improves the acceptance for data delivery. Data coming from different sources should be filtered and homogenized. Under cost efficiency - so <u>much</u> as necessary, so <u>little</u> as possible – is a useful approach in ensuring an appropriate balance in input data is met.

Development of an agreed city-scale groundwater model: good practice

Development of an agreed city-scale model which is coordinated with all users (e.g. Cooperation between authorities and water companies) is also a key point of good practice where multiple users have the same needs or objectives for using a groundwater model (e.g. managing flooding and infiltration drainage in a city) – otherwise individual users develop individual models which might parametrize the groundwater system slightly differently and reach different model outputs. Having a single agreed model between the users in a city avoid different user decisions based on different conceptual and numerical groundwater models with different inputs.

4.3 Workflows of good practice

Good practice in the design of groundwater modelling should include each of the following work-steps – in dependence of the available data and the required accuracy of the model outputs.

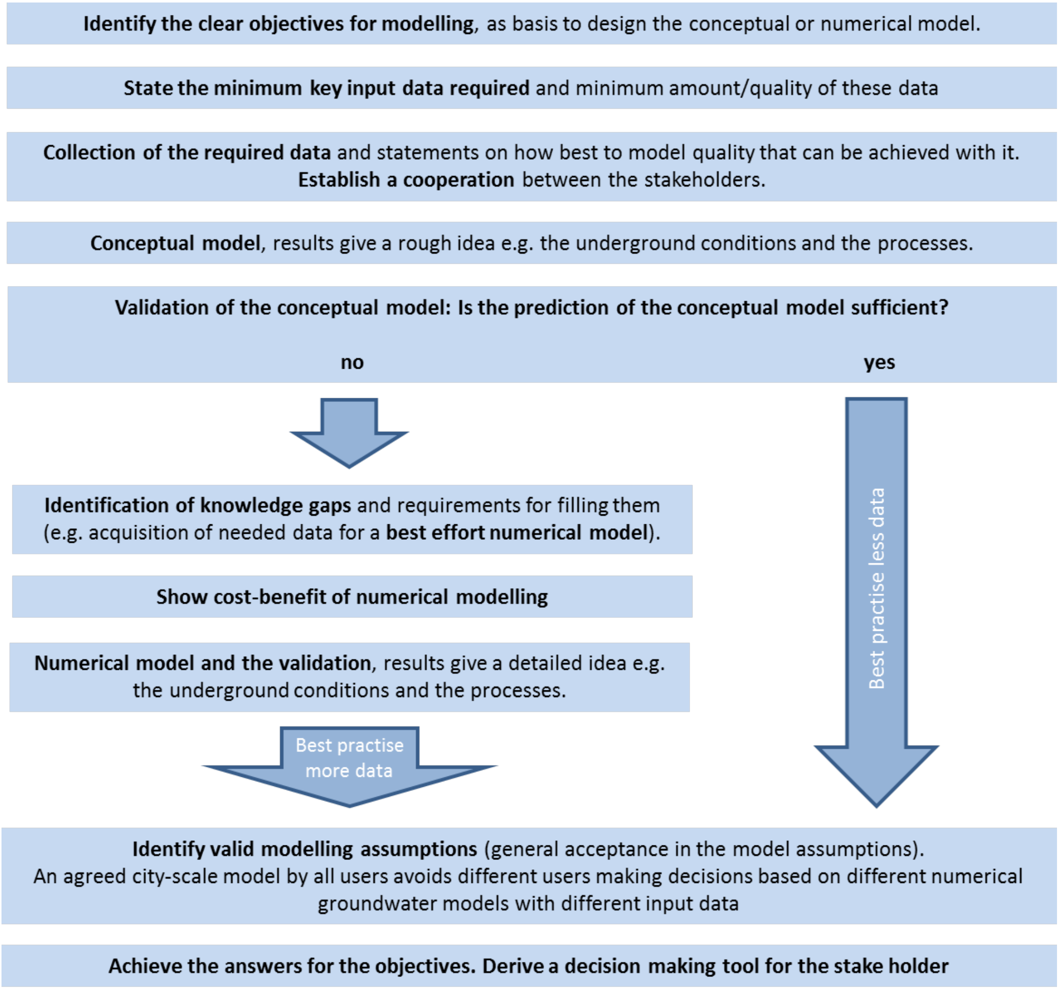


Figure 4.1. A generalised good practice workflows for high and low data availability

4.4 Case studies

Different good practice strategies are determined by different availability of input data in cities. The examples of groundwater models developed for Glasgow and Hamburg are used to highlight the different good practice steps in each case, and these are separated into 'good practice' steps and 'best effort' workflow examples.

Hamburg (Germany) – Good practice developing a standardised city groundwater model between multiple stakeholders

The case study is an example of how groundwater modelling can be used effectively to support city planning and management of subsurface resources. It is also a benchmark example of the interaction and cooperation required between multiple users of a model (e.g. city authorities and the water supplier) to develop an agreed city-scale model for all users.

The groundwater model was developed by the city's public Water Supply Company (Hamburg Wasser) in collaboration with the State Geological Survey (BSU) in the city municipality. The aquifer framework used within the groundwater model is taken from the cities 3D geological model, developed and held by BSU for third party use, and the aquifer parameterization in the groundwater model was developed using data held by both BSU and Hamburg Wasser. The geological model, which was used to inform the geometry and stratigraphy of the aquifer is based on approx. 200 000 boreholes alone, and the 3D numerical groundwater modelling with SPRING (delta-h) software parameterized this geological framework with the cities extensive groundwater monitoring data. However, the outstanding elements of good practice to be taken from the case study are the integration of both public and private datasets within the city to develop a coherent and agreed understanding of the aquifer properties in the city, and how the regional groundwater system should be demarcated to develop appropriate and management groundwater catchment protection areas. Had the groundwater model been developed by either the State Geological Survey, or the Utility company in isolation, the model was not be treated as an accepted or agreed groundwater model by the other, and groundwater management decisions, or city development decisions would be based on separate groundwater models and understanding.

The groundwater model is used to help approve new groundwater abstraction schemes in the city, and also manage the protection of the public supply well fields. The improved understanding of the cities groundwater resource which has been gained from the model, has also underpinned an optimization program of groundwater and surface water monitoring network in the city, which has now been streamlined to 650 monitoring sites for quality and quantity. The Model will be used in the long-term for groundwater protection issues, and as a decision making tool for the groundwater use – public and domestic.

Glasgow (United-Kingdom) – An example of good practice in developing an urban groundwater with low data availability to improve conceptual understanding

The case study is an example of how a robust conceptual groundwater model can be developed to help improve general understanding of urban groundwater resource in the absence of significant aquifer properties data (e.g. urban-scale groundwater flow patterns, general depth to groundwater and characteristics).

Glasgow is underlain by complex quaternary deposits 30 m thick, up to >50m thick across the city. These form a complex shallow aquifer, wherein higher permeability sand and gravel dominated units are laterally discontinuous over 100s meters and are of significant variation in thickness where present. The urban groundwater resource held within these deposits is vulnerable to contamination as a result of the shallow depth to groundwater (<5 m) within the city centre, and the presence of multiple sources of potential pollution (e.g. from shallow mine shafts underneath the city centre, heavy metal soil contamination and buried waste). To be able to manage and protect the resource, as well as meet future legislative requirements of the EU Water Framework Directive, the city municipality and national environmental regulator (SEPA) require a better conceptual understanding of the general characteristics of the urban groundwater resource within the superficial aquifer (e.g. general regional groundwater flow pattern across the city, depth to water table, and seasonal variability of the resource).

There are, however, few observed groundwater levels or aquifer properties data to parameterize an urban groundwater model. The city forms a good case study in this situation where a ‘best effort’ approach can be taken to develop a lower resolution groundwater model, using the input data available to develop a ‘conceptual model’ of the groundwater regime in the city, specifically focused to representing groundwater-levels and recharge – key parameters needed to be understood better to manage and protect the resource in Glasgow. The complex geometry of the superficial aquifer were modeled using the detailed 3D geological-framework modeled from the city’s comprehensive geological model, based on the information of 50 000 boreholes. Aquifer properties were approximated using the few aquifer properties data available, and from more extensive datasets from similar superficial aquifers elsewhere in Scotland. The model was calibrated to groundwater-level observations available (most one-off observations, rather than time series) and river levels (time series).

Whilst the model is not of sufficient resolution to delineate groundwater catchment areas, or protection zones around any potential future public water abstraction in the city – the model is robust enough to enable stakeholder to develop an improved conceptual understanding of the urban groundwater resource to ensure appropriate use and management of the resource at a city-scale (e.g. to help inform where infiltration drainage is inappropriate), and to help inform where future monitoring of the groundwater resource should be focused. With more local data (groundwater level network) and validation of the conceptual groundwater model the information quality provided by the model could be significantly improved in the future. By using the 3D geological model to inform the aquifer geometry and properties modeled ensured the groundwater model was developed from an existing coherent understanding of the cities geology and aquifer, which has been developed by the British Geological Survey, City Council, and several other public and private stakeholders in the city.

Integration of groundwater models to resource management and city planning: good practice

As well as Hamburg, the cities of Ljubljana and Bucharest provide good practice examples of developing groundwater models which are appropriate to city planning needs. These are discussed in turn below, with the different strategies necessitated by the availability of groundwater data in the city highlighted.

Ljubljana (Slovenia) – *good practice example of translation and use of the cities groundwater monitoring network data within a decision support tool to support management and protection of the urban resource*

Following a potentially significant contamination event to the city's urban groundwater resource, which supplies drinking water to the city, the city municipality and geological survey have developed a new decision support system (DSS) for the management of the aquifer. This forms a good practice case study in two respects: 1) that the DDS is based on time series groundwater observation data from the cities monitoring network, and 2) providing a clear example of how groundwater data and knowledge can be translated to support decision making for management of the subsurface and cities resilience.

The groundwater model is based on the MIKE SHE/MIKE 11 modeling software, and simulates the groundwater dynamics and transport of pollutants in the aquifer based on an integrated groundwater/surface water model. A user-friendly graphical interface enables water managers to utilize the database, numerical modeling techniques and expert knowledge, and thus gives them fast and easy access to supporting information for mitigating groundwater pollution.

Bucharest (Romania) – *one of the few cities to have developed a city-scale groundwater recharge and flow model which has integrated subsurface urban infrastructure, to better understand the impacts and interaction of the infrastructure to the urban groundwater resource*

The city of Bucharest forms a best effort example of developing an integrated groundwater recharge and flow model with subsurface urban infrastructure, to understand how the urban recharge regimes are impacted and altered by subsurface infrastructure. This model incorporates the available monitoring network data in the city, and as such Bucharest also form an example of good practice in using and translating groundwater monitoring to support decision making and management of the city's groundwater resource.

In Bucharest urban sewer infrastructure is known to impact the groundwater resource through leakage and new infrastructure has altered the groundwater flow regime in the city. Understanding the impacts of this infrastructure on the urban groundwater resource is important, to mitigate flooding and protect the quantity and quality of the groundwater resource, which supplies the city's public water supply. Urban infrastructure in Bucharest has: 1) led to reduced natural aquifer recharge; and 2) several subsurface infrastructure components provide focused groundwater recharge, such as water supply network losses, and leaky sewer systems.

To help understand these impacts better, and to mitigate impacts of future subsurface infrastructure Bucharest University and the city municipality has developed a groundwater numerical flow model focused on simulating the interaction between urban infrastructure and the groundwater system of Bucharest city. The groundwater recharge regime and influence of different urban infrastructure to the recharge were modelled by parameterizing preferential flow paths and leakage into the groundwater model to simulate the pipelines and conduits of the urban drainage infrastructure (e.g. 3D sewer system and the 3D subway network).

The model has enabled: (1) the detection of the sewer segments susceptible to groundwater infiltration; (2) the detection of the sewer segments susceptible of exfiltration into groundwater; (3) identification of the sewer segments immersed in groundwater totally (about 17km representing 3.5%) or partially (about 80km representing 16.5%); and (4) the quantification of the water exchange between groundwater and the city sewer network.

For more detail to Bucharest city and groundwater issues and resource management please refer to Appendix A3.

Application of groundwater models to understand impact of shallow geothermal schemes in cities: good practice

The cities of Basel and Zaragoza provide good practice examples for the development and parameterisation of groundwater heat-transport models to help understand subsurface geothermal energy potential, and what impact new shallow geothermal schemes may have on the overall resource (Epting et al 2013; Garcia-Gill et al. 2014).

Hamburg is also a key bench example of good practice in this (Bonsor et al. 2013) – here the agreed-city scale groundwater model has been attributed with groundwater temperature data from over 100 boreholes in the city, and the model is used by the city municipality water department as key resource in determining new shallow geothermal scheme applications. The thermal influence and elevated groundwater temperature from deep salt domes in the city's subsurface can be clearly visualized and quantified. The examples of Basel and Zaragosa are discussed in turn below, with the different strategies necessitated by the different drivers and data availability in the cities.

Basel (Switzerland)

3D numerical groundwater flow and heat-transport modeling (FEFLOW©) have enabled quantified understanding of the thermal influences on the shallow unconsolidated urban groundwater body in the city (Epting et al. 2013; Epting and Huggenberger 2013). Using the model it can be demonstrated that the urban thermal groundwater regime is influenced by: (1) urbanization and annual heating periods; (2) thermal groundwater use; (3) seasonal trends; (4) river-groundwater interaction; and (5) climate change and consequences thereof. The model output facilitate the ''present state'' of the urban thermal groundwater regime to be described, and also to derive the ''potential natural state'' of the groundwater body. Furthermore, scenario development facilitates the evaluation of new thermal groundwater and subsurface use as well as potential mitigation measures for the future thermal management of specific regions within the groundwater body. Currently, the developed tools are extended for the thermal management of the various groundwater bodies of the whole city of Basel. The model is also used to help support city management of the groundwater resource (both quantitative and quality) as well as help begin to understand the impact and development of subsurface structures (tunnels, buildings).

Zaragoza (Spain)

A regional 2D model (developed using TRANSIN-IV model code) has allowed the groundwater flow and heat transport processes in the southern part of the city of Zaragoza (80 km2) to be simulated (Garcia-Gill et al. 2014). The modelling has provided understanding and some quantification of the thermal interferences between 28 existent shallow geothermal exploitation systems and the dimensions and cinematics of the heat plumes generated (thermal contamination). The model is calibrated and validated against a high resolution data set obtained from two monitoring networks. The first one is a standard network designed for the management of groundwater resources (head measures and chemical sampling) and the second one consists of a test monitoring network to control the main shallow geothermal installations (temperature). The model has proved useful for the evaluation of the thermal river-groundwater interaction, test concession process protocols for new exploitations and remediation strategies (Garcia-Gill et al. 2014).

Cost-benefit analysis of groundwater modelling for city planning needs: high versus low input data modelling

In view of the small budgets of the most municipalities, it is essential to have cost-efficient tools to assess the service capacity of the underground and manage the subsurface sustainably.

The best-practice approach is an idealised approach with the assumption, that there are extensive data for the model input as well as a lot of time and money. In reality there are good practice and best effort approaches with high and low input hydrogeological data availability, respectively. With high input data availability, detailed high resolution groundwater models can be developed. The output benefit include wider relevance and use of the models for a lot of applications, as well as a greater level of validation of the model and thereby more accurate model outputs and information for different stakeholders, ranging from water managers, city planners and geothermal regulators. The best-effort approach enables process-understanding from only few input-data under the assumption of common principals. However, the limited validation which is possible to these models in the absence of much observational groundwater data means the model outputs cannot be used to support critical decisions on resource management.

Which kind of model will be used of a stakeholder depends first of all on the objectives. If the model is to be used to plan the wastewater pipes for a city for example, a best-effort approach is perhaps sufficient. If there is a need for a model to simulate the complex interactions between surface water and groundwater management, or the impacts of different groundwater abstractions, a higher resolution model with greater input data is necessary.

Figure 4.2 illustrates how the costs and benefits of the different modelling approaches interact, using the examples of Hamburg (high data availability) and Glasgow (low data availability) .

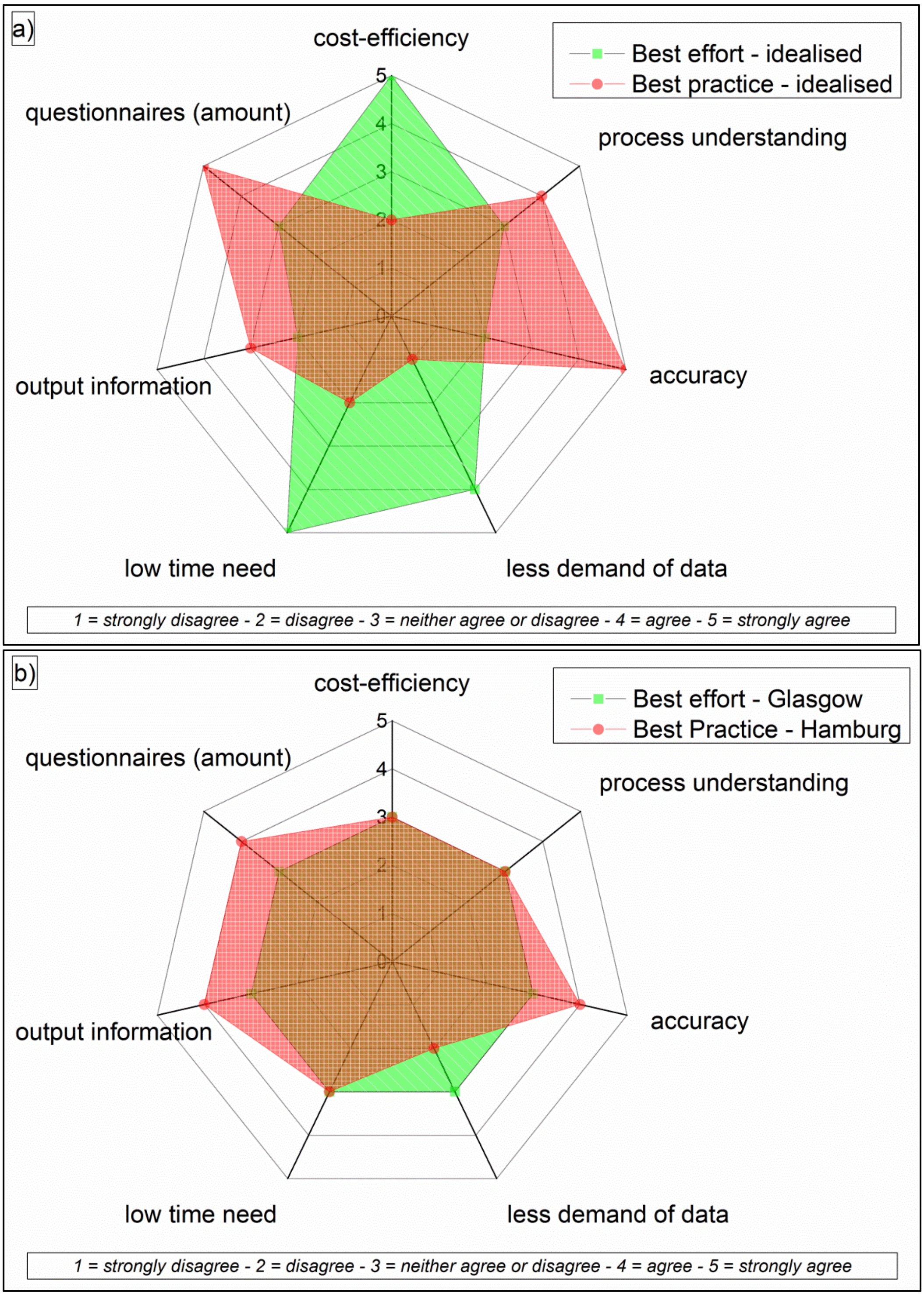


Figure 4.2. The needs and results of the different approaches of modelling; Figure (a) is the idealised scheme for a best-effort and a best-practice approach; Figure (b) shows the scheme for the mentioned models from Hamburg (best-practice) and Glasgow (best-effort).

[cost-efficiency = relationship between costs for modelling/data acquisition and model output; process understanding = can the model contribute for the common process understanding: accuracy = the accuracy of the model output; less demand of data = amount of needed input data; low time need = time consumption for the modelling; output information = amount of model information as output; questionnaires (amount) = how many different kind of questionnaires (water, heat city planning) can be answered by the model]

4.5 Knowledge gaps

Critical knowledge gaps in modelling capabilities limit understanding of urban groundwater resources and subsurface planning at present and include:

- Inclusion of Made (artificial) Ground and subsurface infrastructure into groundwater models
- Modelling the linkage of seal-level change to groundwater-levels in coastal cities
- Integrating real time monitoring data into groundwater models, to enable forecasting and prediction for city planning
- Adequate monitoring systems to provide required data to develop calibrated and validated flow and heat transport models

ID	Current State	Desired State	Gap Description	Gap Reason	Remedies
1	The made ground (artificial) as well as the subsurface infrastructure is not implemented often in the groundwater models	Groundwater models with all required input data to model the groundwater behaviour more accurate	Inaccurate groundwater models concerning the missing input data	The location of artificial made grounds are not mapped and the data of the infrastructure are distributed to different authorities or public utilities	The mapping of the made ground and the data exchange with the public utilities and the implementation of these data into the model
2	Most models do not consider the linkage of sea-level change to groundwater-levels in coastal cities or the interaction between the surface water and the groundwater	Consideration and modelling of the interaction between the groundwater and surface water bodies	Fluxes (e.g. heat or mass) cannot be modelled accurate at the boundary layers	The data collection is difficult because the fluxes are transient	It is necessary to examine and describe the influences and interactions of the neighbouring water bodies to the groundwater bodies by a further conceptual model
3	The most city-scale models are steady-state models and forecasts and predictions are not possible	Integrating real time monitoring data into groundwater models, to enable forecasting and prediction for city planning	Potential changes of the input parameters cannot modelled as a prediction or forecast	Change the steady-state model to a transient/dynamic model	For the transient model dynamic data are required and the knowledge of the processes and interactions must be present
4	The monitoring systems in the most cities are insufficient to get accurate groundwater models	Adequate monitoring systems to provide required data to develop calibrated and validated flow and heat transport models	The monitoring network is not dense enough to get spatially highly resolved input data for accurate models	Insufficient monitoring network for the groundwater	Implement a monitoring network in the cities with a high temporally and spatially resolution

5. Effective knowledge exchange: translating groundwater and geothermal data to city planning

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Key words: knowledge and communication gap; closing knowledge and communication gaps for subsurface planning; knowledge exchange practices; decision support tools; translating subsurface knowledge

5.1 Fundamental knowledge and communication gaps

The value of good practice to develop robust, systematic, subsurface environmental datasets in urban areas is undermined if the data are not communicated and translated effectively to city municipalities to support environmental management and city planning.

City planners and municipalities face an increasing range of issues and problems in management of the urban environmental. With increasing urbanization, and climatic variability, management of cities, and the people, infrastructure and environment is not just increasingly difficult but also important, and there is increasing need to better utilize available datasets in planning processes. A critical, condition for this is the flow of information between scientists and decision-makers. This is often not always achieved, and rarely in an effective and timely manner for decision making processes. In most cases, this is not a reflection of an absolute lack of information of knowledge of the urban subsurface, but the limited data and knowledge exchange between subsurface specialists and decision makers. The underlying reasons behind this communication gap are many. Often environmental data and hydrological modeling are only communicated as a hard-science numerical approach, which is difficult for non-experts to understand (Jacobs 2002; Rayner et al. 2005; Martínez-Santos et al. 2008; Liu et al. 2008; Molina et al. 2011). Scientific input is often ignored by decision makers because critical information is not presented in a usable form and is therefore not available or accessible to them. There is an obvious need to adapt research results to be more understandable and usable for subsurface planning and the groundwater and geothermal resources held within it.

Within Europe, and in many parts elsewhere in the world (Lavoie et al. 2013), the fundamental knowledge and communication gap between subsurface environmental specialists and city planners, generally leads to the subsurface being overlooked in planning processes, and management of the subsurface environment is ad-hoc. Planners are often not aware of the opportunities held by the subsurface for urban development (e.g. sustainable drainage, shallow geothermal energy potential, seasonal heat storage and space), or what data need to be acquired during the planning process to assess these opportunities, and manage groundwater and geothermal resources sustainability (GCC 2012). Equally, there is insufficient awareness and understanding in geological surveys, as to what subsurface data is required by city planners, in what formats, and at what stages in the planning processes.

The effect of these data and knowledge gaps are exemplified by there being no systematic local or national planning guidance for the subsurface environment in the UK, or worldwide. Geological surveys have a key role to play in providing appropriate environmental data and knowledge to underpin city planning and the management of subsurface resources, to ensure they can be utilised effectively, and sustainably, to support future cities. Bridging this current fundamental knowledge gap is increasingly important as the world's population becomes increasing urban. Indeed, projections estimate more than two-thirds of the world's population will live in cities by 2050 (UN 2012).

During the last 2-3 decades geological surveys have invested significant focus to developing 3D geological models, ground water models and interpreted maps, at a range of scales, in order to raise the level of knowledge and improve the basis for planning and support decision making. But, despite the development of more maps and models, a significant and fundamental gap in knowledge of the subsurface still exists between the specialists and the planners, decision makers and politicians. The subsurface is very much 'out of sight and out of mind'.

How might this knowledge gap be bridged?

There is growing recognition of the extent to which the knowledge gaps limits effective management of resources and the city environment (Janža 2015; Lavoie 2015). Different cities within Europe are now beginning to try different approaches bridge the gap, and enable subsurface specialist to better communicate both the content, and relevance, of subsuface data to city planning processes. Within the UK, the National Environmental Research Council (NERC) and Innovate UK have recently funded two Knowledge Exchange Fellowships for 3 years to provide knowledge translators between the different specialisms, and to ensure available UK subsurface data held by NERC are visible and relevant to subsurface planning. Within Ljubljana (Slovenia) an adavanced decision support tool has already been developed between groundwater specialists and city authorities, to assist manaagment of urban contamination and protection of the public water supply from the urban groundwater resource. The Geological Survey of Denmark is also working towards developing more user relevant visualisation and decision support tools with city municipalities and water sector companies. These are discussed in more detail as examples of different good practices to bridge the knowledge gap.

5.2 Emerging good practice – case studies

Odense, Denmark – *developing cross-specialist working groups within the city municipalities and working groups and visualisation tools*

To help build the communication and knowledge gaps between different specialists (including planning, project design and management, engineering, architecture, geologists) Odense has aspired to develop a **S**ubUrban **I**nfra-Structural **P**lanning-group (SIP-group), which will involve a wide range of specialists within the city municipality. The ultimate aim of the work is that this SIP-group will enable the communication gaps to be properly addressed, and new long-term knowledge exchange pathways to begin to developed between different specialists and city planners, to so that the 3D model does not just become another map or model of subsurface data which is not relevant or accessible to city planners and environmental management.

Specific working groups are also being used to develop shared expertise and understanding between specialists within specific topics. A key example is for greater co-ordination and improved management of groundwater resources in the city – often a resource which is overlooked in planning processes. A working group composed of individuals from Odense city municipality, Geological Survey of Denmark (GEUS), VCS Denmark (public water supply), and Alecta and I-GIS software companies, has been developed to this end, which a specific aim of developing an improved visualisation and communication decision support tool for groundwater. The aim is to develop “a 3D geological/hydrogeological model as the basis for understanding the urban water cycle”, and for this model to develop a mechanism or processes which can be emulated for other subsurface datasets and end users. The model developed will be tested by the SIP, and critically in doing this, to begin to bridge the wider connection between the decision makers and the specialists in the SIP-group.

Glasgow, UK – *Research Council and Business sector Knowledge Exchange Fellowships to increase awareness of subsurface data and resources in planning and urban development processes*

A similar approach to that of Odense is being taken in the UK to try to address the communication and knowledge gap surrounding subsurface resource utilisation and management within urban development and planning. In the UK, there are increasing efforts to develop cross-discipline working groups to help transfer data and knowledge between disciplines. In Glasgow, work is being undertaken to embed the lessons learnt from these working groups into Supplmentary Planning Guidance, so that subsurface data are reported fully compliant to existing industry best practice to increase interoperability of data, and to increase the utilisation of subsurface data in strategic development planning processes in urban areas, and re-used to much greater effect by different stakeholder in construction and development projects.

The work is being supported by two Knowledge Exchange Fellowships over the next for 3 years by the National Environmental Research Council (NERC) and Innovate UK. The fellows primary aim is to act as knowledge translators between different specialisms, to help identify and forge new knowledge pathways between different subsurface specialists (e.g. construction industry, engineers, geologists, hydrogeologists) and above-ground development and planning specialists (e.g. engineers, archtiects, and planners) – akin to the SIP-group proposed in Odense.

The NERC KE Fellowship work is trialling the development of the UKs first local government fully integrated above and below ground BIM (Business Information Model) to help highlight the available geological and groundwater/geothermal data available to a contruction and urban development projects, within the city of Glasgow, from the planning and design phase right through to the construction and completion stages. This BIM is being developed and trialled by local government, with engagement from key private and public sector stakeholders. Like Odense, the aim is that the 3D BIM will be developed so as to be an effective tool at highlighting subsurface data, and it will be relevant and used to inform city planning and management, rather than be just another 3D model which only bridges the gap half way.

The work is initially being trialled in Glasgow, but the role of the Fellowships is try to transfer the succesful knowledge exchange mechanisms trialled to other cities and national-level stakeholders in the UK.

Ljubljana, Slovenia – *developing decision support tools (DSS), incorporating time series monitoring data of key resources*

The city of Ljubljana in Slovenia has been able to develop a specific decision support tool to inform appropriate courses of action in the event of contamination events. This DSS integrates groundwater monitoring data with geological and hydrogeological data, to inform the water utility company and regulators appropriate remediation actions to protect the city's groundwater-sourced public water supply in the event of a contamination event. The development of this tool was driven from a contamination event which threatened the city's water supply several years ago and highlighted the need for authorities to have better access to the cities groundwater data; existence of legislative and regulation does not in itself to informed resource management (Jamnik et al. 2012).

The system was developed within the framework of the project INCOME (LIFE07 ENV/SLO/000725; http://www.life-income.si/) by Geological Survey of Slovenia in cooperation with project partners (Anton Melik Geographical Institute SRC SASA, and Environmental Agency of the Republic of Slovenia) and end-users (co-financers) Municipality of Ljubljana and Ministry of the Environment and Spatial Planning and Vodovod-kanalizacija, a public company for water supply. The features of the system were defined on the stakeholders meetings and workshops (Janža 2015).

A user-friendly graphical interface enables water managers to utilize the database, numerical modeling techniques and expert knowledge, and thus gives them fast and easy access to supporting information for mitigating groundwater pollution. It consists of three logically interlinked components: the database, hydrological model and decision model.

Database enables the storage, retrieval, display and manipulation of data related to the groundwater resources used for drinking-water supplies to Ljubljana. Through the establishment of an internet application, a larger part of the database is freely accessible through a web viewer (http://akvamarin.geo-zs.si/incomepregledovalnik/). It contains three types of data related to the monitoring, potential sources of pollution and hydrogeological conditions.

The **hydrological model** is an essential part of the DSS. It is a mathematical representation of the hydrological system of the study area, based on the MIKE SHE/MIKE 11 modeling framework (Graham and Butts 2005; DHI 2011a,b). A transient groundwater/surface water integrated modelling system enables simulation of the groundwater dynamics and the transport of pollutants in the aquifer. The most important feature implemented in the DSS is the simulation of the propagation of pollutants in the aquifer.

The **decision model** comprises a set of logical rules formalizing the knowledge and experiences of water managers and hydrogeologists related to emergency activities. A wide range of possible scenarios for activities to be taken in the case of discovery of pollution in the groundwater was analysed. Upon this basis, conditions and recommended actions or responses were defined. Syntax was developed which enables the easy creation and implementation of changes in the decision model.

The main advantage of presented DSS is reduction of the quantity of input data required and the modelling steps required to achieve an understandable level for water managers. In a similar manner, the model outcomes are presented in the form of a simulated traveling time of the pollution plume to the abstraction well, and the pollutant concentrations in the abstraction wells. In this way, DSS simplifies the use of the model and provides water managers with model outcomes in an understandable form that bridges the often-mentioned gap between science and decision making that hinders more efficient use of hydrogeological data and numerical modelling in water management.

The use and sustainability of the system (or its parts) after the project end have been assured in different ways:

- The project database that is freely accessible through a web viewer has been maintained by geological Survey of Slovenia. The long term maintenance and update of monitoring data is going to be assured by incorporation of the project database into a common environmental data base of Municipality of Ljubljana. The process is in progress at the time.
- The constructed hydrological model is based on the state of the knowledge of hydrogeological conditions in the study area. Recently it was used (by Geological Survey of Slovenia) for groundwater residence time simulations and new delineation of production well catchment areas into protection zones which were implemented in Decree on determining the drinking water protection area for the aquifer of Ljubljansko polje (OG RS, 2015).
- The full form DSS for emergency response to groundwater resource pollution has been used only for the study case scenarios. Luckily no real threatening pollution has occurred after the construction of DSS, but the system and the team of experts of Geological Survey of Slovenia and Vodovod-kanalizacija, a public company for water supply are prepared to use it also in real case scenarios.

The tool is specific to the city of Ljubljana, however, dependent of the city drivers and data availability. As yet, there are no knowledge exchange pathways being developed for other cities to replicate the work, as national tool for city regions. This upscaling of the knowledge and data exchange pathway is the critical next step for Slovenia as in many other countries worldwide, where there are multiple cities with examples of good practice of knowledge translation (see table below) but very few, if any, have transferred and developed these to cities nationally.

Other examples of good practice of integration of groundwater information into decision making for groundwater management:

	Hydrogeological information/tools/methods	City/region (references)
Level of interpretation and adaptation of hydrogeological information for GW management and land-use planning LOW	Monitoring/Measured data (GW levels, temperature, chemical parameters, hydraulic conductivity, transmissivity…)	database accessible through a web viewer: Amsterdam (https://maps.waternet.nl/kaarten/peilbuizen.html The Hague (https://wareco-denhaag-public.munisense.net/ Ljubljana (http://akvamarin.geo-zs.si/incomepregledovalnik/)
	Hydrogeological maps / conceptual models / 3D models	Bucharest (Serpescu et al., 2015) Glasgow (Turner et al., 2014) Ljubljana (Janža 2009) Netherlands (Gunnink et al., 2013)
	Numerical GW flow/heat-transport models	Bucharest (Boukhemacha et al., 2015) Glasgow (Turner et al., 2014) Hamburg (Taugs et al., 2014) Ljubljana (Janža et al., 2011b) Basel (Epting and Huggenberger, 2013) Zaragoza (García-Gil et al., 2014)
	Vulnerability maps	Ljubljana (Bračič-Železnik et al. 2005) Sierra de Canete (Jiménez-Madrid et al., 2012)
	Geothermal potential maps	Barcelona (García-Gil et al., 2015) Basel (Epting and Huggenberger, 2013) Berlin (Kastner et al., 2013) Ludwigsburg (Schiel et al., 2016) Netherlands (http://www.thermogis.nl/)
	GW contamination risk maps	Multicriteria analysis method : Canada (Lavoie et al. 2015)
	Regulations based on zoning (e.g. GW protection zones)	Methodology: Slovenia (Brenčič et al. 2009) Spain (Jiménez-Madrid et al., 2012) Switzerland (BUWAL, 2004) UK (Carey et al. 2009)
HIGH	Decision support tools (e.g. computer tools integrating numerical models	DSS for emergency response to groundwater resource pollution: Ljubljana (Janža 2015) DSS for land-use planning: Monroe County, Michigan (Reeves and Zellner 2010)

5.3 Knowledge gaps

Critical knowledge and technical capacity which limit communication and understanding of urban above and below ground resources and interaction in city planning include:

ID	Current State	Desired State	Gap Description	Gap Reason	Remedies
1	scientific input (subsurface information) is often not included within decision making /planning processes	decision makers /planners use up to date (state-of-the-art) information and knowledge available – and scientists have up to date knowledge of policy needs	procedures (guidance) for use of subsurface information in planning are not well defined, and lack of awareness of available information	critical information is not presented in a usable form and is therefore not available or accessible to them	better communication between different specialists, multidisciplinary working groups, DSS tools
2	Critical knowledge and communication gap between scientists and planning	Strong two-way communication between both parties, to mutually inform	Lack of awareness of shared needs and knowledge between the two disciplines, and of the existing data and knowledge within each	Disciplines have historically worked independently of each other	Establishment of cross-discipline working groups to discuss on going work within a city, and shared knowledge needs and knowledge/data assests

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Appendix A3. 1 Bucharest Urban Groundwater Monitoring System

Bucharest City area covers around 240 km^2 (6 districts). Hydrological features, playing an important role in the water balance of the city, must be mentioned. Two rivers are crossing the city, both having gone through extensive modifications. The northern river (Colentina) is landscaped in a series of lakes communicating directly with the shallow aquifer. The southern river (Dambovita - crossing the center of the city) is channelized thus interrupting the communication with the aquifer. This river is connected to an important artificial lake (Lacul Morii), located in the western part of the city, constructed in the ‘70 for flood management and urban landscape improvement. Also, a significant number of artificial and natural lakes comprising around 11 km^2 are spread on the city surface.

The geological setting is represented by Quaternary sediments (clay, loam, marl, loess, sands and gravel) either fluvial, lacustrine or eolian. From the Lower Pleistocene (200 -150 bgs) to the latest Holocene deposits, three important aquifer formations are representative for the Bucharest area: (1) the deeper aquifer - used for water supply, (2) the medium depth aquifer - also used for water supply in some cases, and in a direct (natural and anthropogenic) hydraulic connection with the (3) shallow aquifer (in direct connection with the underground infrastructure).

The Urban Groundwater Monitoring System (UGMS) of Bucharest City tries to capture the most important urban hydrogeological characteristics. The development of the UGMS took into account several constrains and requirements specified in Table 1.

Table 1 - Requirements and constrains of the UGMS

REQUIREMENTS	TYPE	SOLUTION
Coverage area	**Geometry - Location**	The distribution of the UGMS points covers around 110 sq km (Figure 1), almost a half of the administrative area of Bucharest City.
Target aquifers		The UGMS is a monitoring system defined for the urban aquifer system. In this sense, the impact upon the deeper aquifer can be considered in relationship with water extraction and in some cases with pollution, due to inadequate drilling procedures. Considering these arguments and taking into account the development costs, UGMS focuses only on the first two aquifer layers (Colentina - shallow aquifer and Mostistea - medium depth aquifer). The number of monitoring points for the shallow aquifer is larger (116 points) than for the medium depth aquifer (only 30 points), due to the fact that the shallow aquifer shows a strong interaction with the urban infrastructure.
Special urban infrastructure features		The specificity of an urban groundwater monitoring system is to capture the impact of urban infrastructure effect upon groundwater. To accomplish this task, many of the monitoring points are located in the vicinity of the Dambovita lined-up channel and of the Lacul Morii lake. Other special urban infrastructure elements (subway line, deep foundations, others) also have monitoring points in their surrounding areas.

Parameters and tests	**Data**	Each project involves a limited budget. In order to optimize it, a certain balance between the drilling procedure, well equipment, laboratory and in-situ tests must be taken into account. The UGMS developed in two different phases, using two different drilling procedures. In the first phase the wells were done using hydraulic rotary drilling (around 34 monitoring points) and in the second one, using auger drilling with protective casing. The parameters and the data collected during and after the development of the monitoring wells are described in Table 2.
Monitoring parameters		Hydraulic head data, water sampling and laboratory analysis represent the needed information. In order to reduce the costs and to maximize the data benefit, several monitoring boreholes were equipped with double tubing targeting both aquifers. The sealing between the two aquifers was made of a mixture of clay, bentonite and cement.
CONSTRAINS	**TYPE**	**SOLUTION**
Security and well integrity	**Geometry - Location**	Security of the monitoring points is a key aspect in an urban environment. There are several areas of social triggers that need careful attention: (1) scrap iron black market - in this case the metallic components (well head protection) must be eliminated or somehow hidden - for UGMS most of the metallic components (well cover) are found at ground level in public places, (2) vandalism - there is no real solution regarding the public places (ex. UGMS lost around 6 monitoring points due to vandalism - wells were filled with stones and other materials, the well casing broken and the cover stolen). The general solution, to avoid these risks, was to set up (as much as possible) the monitoring points in private locations belonging to the municipal water company.
Budget	**Data**	The budget limitation is a constrain for any project. Within the available budget, the UGMS had to respond to two needs: (1) characterization of the aquifer media - around 10 hydrogeological cluster points, located in key points of the city and (2) hydraulic head monitoring points (double tube wells).

Table 2. Drilling procedures - advantages and disadvantages

No.	Parameters - Data - Test	Hydraulic rotary drilling	Auger drilling
1	Lithology description	+	+++
2	Granulometry	+	+++
3	Electric resistivity (16, 64 Ωm)	+++	-
4	Natural Gamma (Api)	+++	+
5	Temperature	+++	+
6	Hydraulic pumping test	++	+++
7	Slug test	+	++
8	Level measurements	+++	+++
9	Chemical parameters	++	+++
	Legend - Not applicable | + Satisfactory | ++ Good | +++ Excellent		

The urban groundwater monitoring system in Bucharest is composed (end of 2014) by a total number of 145 monitoring points/stations. The distribution of the monitoring points (Figure 2) is concentrated in the center of the city, along the channelized Dambovita River. This can be explained by the high density of urban underground infrastructure elements found in the area: (1) the channel of the Dambovita river, (2) the main sewer collector of Bucharest City located under the channel, (3) 2 major wastewater conduits located in parallel to the Dambovita river, (4) the subway line, (5) Dambovita channel left bank drain and (6) a new drainage system that will be implemented (currently under construction) on the channel right bank.

The monitoring stations/points are divided in three types (Figure 1):

(a) Single point monitoring well - this type is a simple hydraulic head monitoring well with an outer diameter (OD) between 90 - 114 mm. For almost all of these monitoring points, geophysical logging and hydraulic testing (pumping tests for 114 mm OD and slug tests for 90 mm OD) have been performed. In some cases, samples from the aquifer strata (sand and gravel) were collected to determine the granulometry.

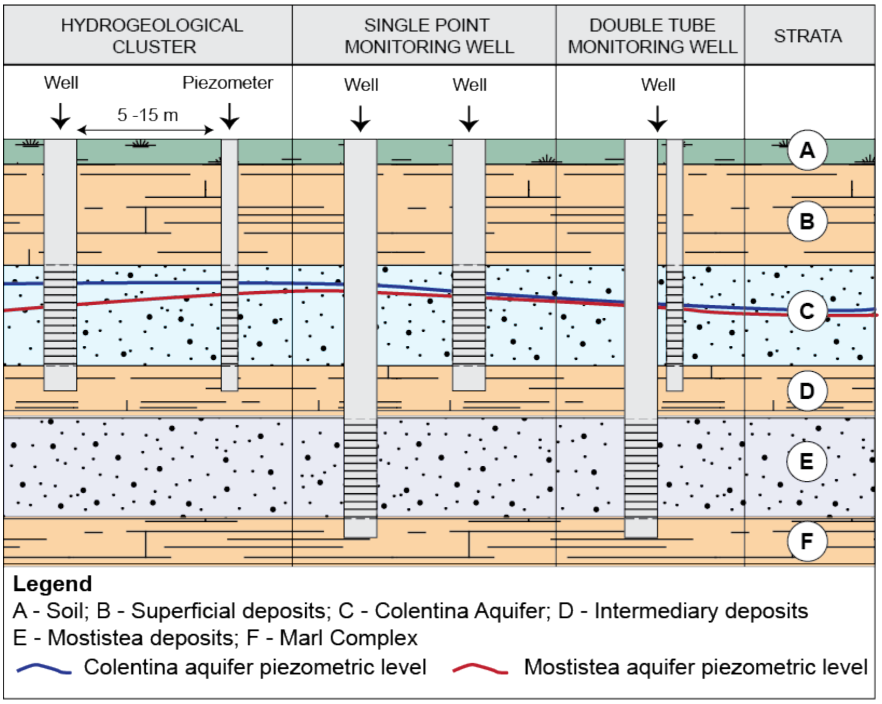

Figure 1 – Types of the groundwater monitoring stations

(b) Double tube monitoring well - this type of monitoring station is designed to measure the hydraulic head for both Colentina and Mostistea aquifer strata. There are two installed tubes in the borehole: 90 mm and 32 mm. For both, slug tests as well granulometric analyses were performed.

(c) Hydrogeological cluster - this type of monitoring station is composed by a well (140 mm OD) and a piezometer (90 mm OD) targeting the same aquifer unit (the distance is between 5 to 15 m). This type of monitoring station was designed to give a proper description on the hydrogeologic parameters by performing pumping tests.

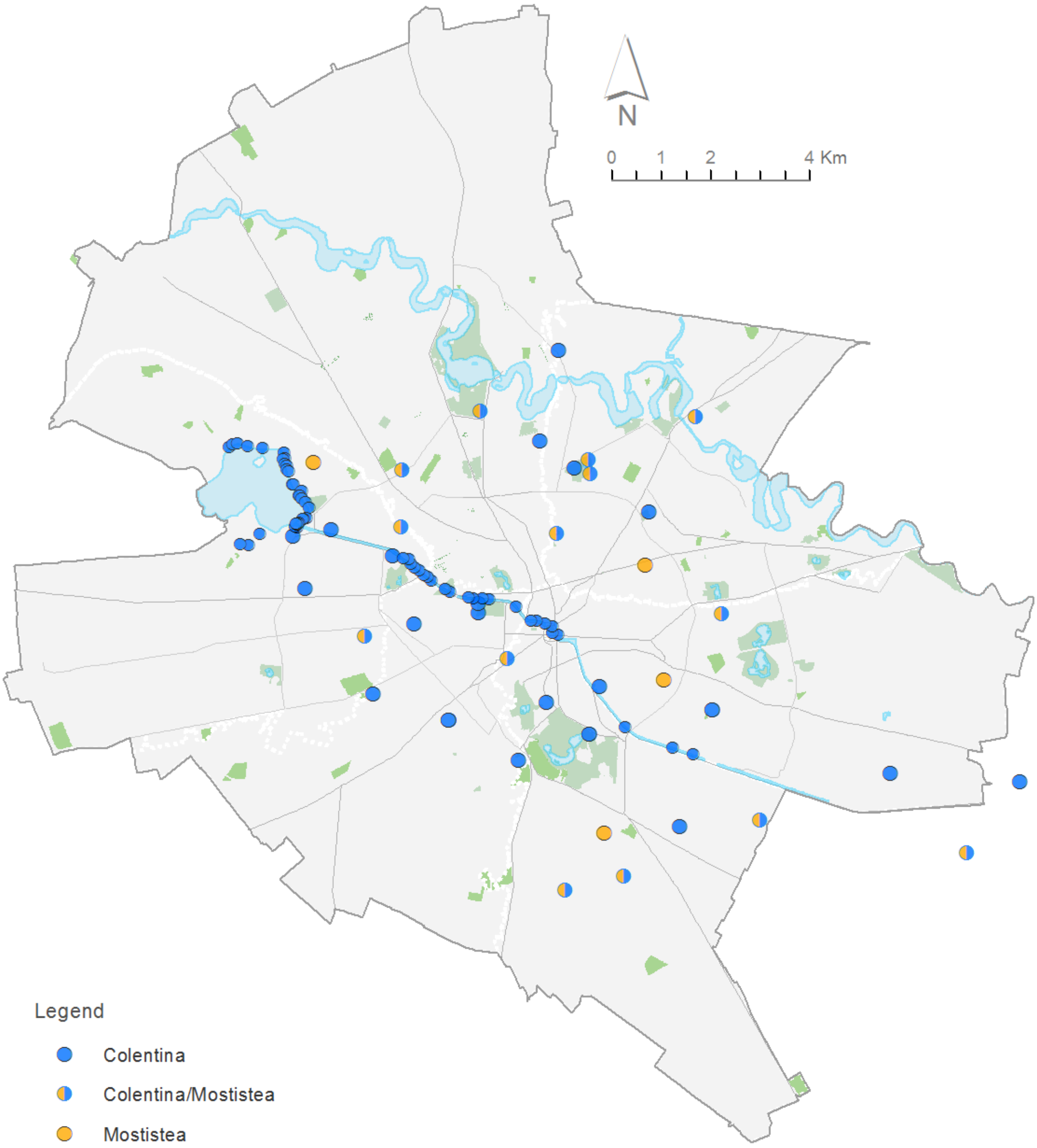

Figure 2. Bucharest City Urban Groundwater Monitoring System